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CLIMATE AND ECOSYSTEM SERVICE BENEFITS OF FORESTS AND TREES FOR AGRICULTURE

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CLIMATE AND ECOSYSTEM SERVICE BENEFITS OF FORESTS AND TREES FOR AGRICULTURE

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ABBREVIATIONS

ACGIH	American Conference of Governmental Industrial Hygienists
BBVA	Banco Bilbao Vizcaya Argentaria
BSA	Biodiversity Strategy and Action
BVOC	biogenic volatile organic compound
CAFE	Carbon, Aqua, Fire & Eco-resilience
CBT	core body temperature
CGRAP	Continental Green Recovery Action Plan
COAG	Committee on Agriculture
COFO	Committee on Forestry
COPD	chronic obstructive pulmonary disease
DSS	decision-support systems
ETF	enhanced transparency framework
FFS	Farmer Field Schools
FLR	forest and landscape restoration
GCAD	Global Cropland Area Database
GGA	global goal on adaptation
HI	Heat Index
IDB	Inter-American Development Bank
IFC	International Finance Corporation
IPC	Integrated Food Security Phase Classification
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
IPPC	International Plant Protection Convention
ISO	International Organization for Standardization
LST	land surface temperature
MEL	monitoring, evaluation and learning
MRV	measurement, reporting and verification
NIOSH	National Institute for Occupational Safety and Health
NWFP	non-wood forest product
PES	payments for ecosystem services
REDD	Reducing emissions from deforestation and forest degradation in developing countries
SIWI	Swedish International Water Institute
SOA	secondary organic aerosol
TFFF	Tropical Forest Forever Facility
UNZA	University of Zambia
UPV	Polytechnic University of Valencia
USDA	US Department of Agriculture
VPD	vapour pressure deficit
WBGT	wet bulb globe temperature

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EXECUTIVE SUMMARY

FORESTS AND TREES CAN BE POWERFUL ALLIES FOR AGRICULTURE

Promoting synergies between forests and agriculture is essential for sustainable agrifood system transformation. Agriculture and forests are often viewed as competing land uses with perceived trade-offs especially stark in regions where land is scarce or highly coveted for agricultural production, fuelling debate on how best to balance food security and forest conservation. Yet, a growing body of evidence demonstrates the many ways that forests and trees enhance agricultural productivity and resilience.

This technical report, a collaboration between the Food and Agriculture Organization of the United Nations (FAO), Stockholm Environment Institute (SEI), The Nature Conservancy (TNC) and Conservation International (CI), synthesizes the latest scientific evidence on a range of climate and ecosystem service-related benefits that forests and trees provide for agriculture. It specifically examines their role in regulating climate, rainfall and water availability at multiple scales, impacting the productivity and resilience of crops and rural workers, and supporting pollination, soil and pest management. This report shows that, together, these ecosystem services are vital for supporting agriculture across a diversity of contexts.

FORESTS MODERATE TEMPERATURES, SUSTAIN RAINFALL AND REGULATE THE WATER CYCLE

Forests play a critical role in regulating climate at multiple scales. They moderate temperatures, sustain precipitation and reduce the impacts of droughts, thereby directly supporting agricultural productivity and resilience. In addition to carbon sequestration and storage, forests provide global cooling benefits through evapotranspiration and via their physical structure and chemistry. Tropical forests, in particular, produce a strong net cooling effect. The conversion of tropical forests to farmland has been shown to reduce evapotranspiration by about 30 percent in Brazil, causing significant local temperature increases. Conversely, restoring 50 percent of deforested land can reverse this trend and lower land surface temperature by 1 °C.

Forests also sustain rainfed agriculture. Through evapotranspiration, forests increase downwind rainfall and also regulate its variability, sustaining atmospheric moisture during droughts and providing a consistent flow of moisture to agricultural areas. At the global level, a recent study shows that agricultural areas in 155 countries rely on forests in other countries for up to 40 percent of annual precipitation. At the regional level, the Congo rainforest, recycles over 40 percent of its moisture locally and contributes over 10 percent of precipitation to remote African agricultural areas.

Forests regulate water quantity, quality and timing. Forests and trees – on or nearby agricultural land, but also hundreds of kilometres away – can provide a range of water-related ecosystem services critical for agriculture, including freshwater supply, regulation of water flows, water damage mitigation, and water purification. The water-related ecosystem services from trees and forests to agriculture are insufficiently monitored and valued, however, which means that they are underrecognized in the agricultural sector and agriculture-related policies, resulting in economic losses for farmers and countries. An integrated approach to water and land management at various scales is essential for ensuring that the benefits of forests and trees for agriculture are optimized.

FORESTS SUPPORT THE WELL-BEING OF RURAL WORKERS

At the local scale, forests create cooler microclimates via shading, evapotranspiration and canopy roughness. These cooling benefits reduce heat stress for crops and rural communities, safeguarding the health and productivity of rural workers by mitigating heat-related health risks. Rising temperatures due to climate change and local deforestation pose a compound threat to the provision of the services of forests and trees for agriculture.

Clearing forests removes shade and evaporative cooling, causing land surface temperatures to rise, often by several degrees across tropical regions, and up to 3–5 °C locally in the Amazon, creating hotter microclimates where people live and work. Temperature increase due to deforestation can in turn impact human health. Between 2001 and 2020, tropical deforestation is likely to have contributed to around 28 000 additional heat-related deaths annually, suggesting that forest loss is both an environmental issue and a potential public health threat.

Forests can sustain local cooling, reduce heat-related health risks, and preserve economic productivity, making forest conservation an essential climate change adaptation strategy, particularly for rural workers with fewer adaptation options.

FORESTS AND TREES PROVIDE OTHER ECOSYSTEM SERVICES FOR AGRICULTURE

Forests and trees deliver other vital ecosystem services – such as pollination, biological pest control, nutrient cycling, erosion control, fodder, mulch, and climate regulation – that enhance crop yields and sustain ecosystem health. Fields near forests may benefit from stronger ecosystem services, especially pollination and biocontrol, but may also experience disservices such as increased exposure to certain pests.

Integrated approaches strengthen climate resilience and food security. Incorporating forests and trees into agricultural systems – as shelterbelts, riparian buffers and forest patches – can reduce dependence on synthetic inputs, enhance resilience

to climate variability, and support the production of diverse, nutrient-dense foods. Integrated approaches can also help maximize synergies and reduce trade-offs among different ecosystem services.

PATHWAYS TO PROMOTE THE BENEFITS OF FORESTS AND TREES FOR AGRICULTURE

Turning knowledge into action is imperative but challenging, since the way in which forests and trees influence agriculture depends on contextual factors like location, distance and pattern. Furthermore, many ecosystem services from forests flow across spatial and temporal scales with services generated in one forest location benefiting agriculture in another. Such cross-scale dynamics highlight the importance of coordinated governance, landscape-scale planning, and institutional cooperation across jurisdictions to enhance synergies and manage trade-offs.

Policy and incentives must bridge sectors, recognizing sustainable forest management as a multisectoral strategy for food security, public health and climate resilience. Global policy processes – in the context of the Paris Agreement, the Kunming–Montreal Global Biodiversity Framework and the joint work on forestry and agriculture linkages by the FAO Committees on Agriculture and Forestry – provide avenues to embed these benefits in national commitments, policies and plans. Incentivizing and valuing forest benefits building on existing initiatives and innovative finance instruments can accelerate uptake. Finally, empowering local farmers, communities and Indigenous Peoples through co-designed solutions, and informing monitoring and models, will be key to achieving holistic, evidence-based outcomes across scales.

Forest conservation, restoration and sustainable use are sound investments in climate-resilient agriculture, rural livelihoods, and global food and water security. By promoting forest–agriculture synergies, societies can work towards a more productive, sustainable and equitable future for all.

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CHAPTER 1

Forests and trees: powerful allies for agricultural productivity and resilience

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Sustainable food systems hold immense transformative potential by offering bold solutions to some of the world's most pressing and interconnected challenges from food insecurity, malnutrition and climate change to biodiversity loss and environmental degradation (FAO, 2021). Tackling these complex challenges demands a fundamental reimagining of how current food production systems are structured and managed. Calls for this transformation have been increasingly echoed at the highest levels of global sustainable development discourse as evidenced by the FAO Strategic Framework 2022-31 and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES, 2024), among others. The role of forests and trees in providing broad climate and biodiversity benefits is a critical component of agrifood system transformation.

Agriculture and forests are often viewed as competing land uses. The expansion of agricultural land has contributed to deforestation (Pendrill *et al.*, 2022), and efforts to protect forests are often framed primarily in terms of conserving biodiversity and storing carbon. The perceived trade-off between agriculture and forests can be especially stark in regions where land is scarce or highly coveted for agricultural production, fuelling debate on how best to balance food security and conservation (Ickowitz *et al.*, 2022). Yet, this view overlooks the growing body of evidence that shows the many ways in which forests and trees, under the right management strategies, can be powerful allies for agriculture. Forests and trees can increase crop productivity, climate resilience and rural well-being (Dainese *et al.*, 2019; Ickowitz *et al.*, 2022; Lawrence and Vandecar, 2015). Harnessing these benefits requires moving beyond a narrow conservation agenda towards integrated strategies that work for both farmers and ecosystems.

The protection, restoration and sustainable management of forests in landscapes are crucial for climate change mitigation because forests store large quantities of carbon in their biomass and soils. The role of forests in climate regulation, however, goes beyond their carbon storage capacity to include their significant cooling effects, which are largely unrecognized (Ellison, Pokorný and Wild, 2024; Seymour, Wolosin and Gray, 2022). Forests and trees (see the definitions of forests and trees in **Box 1**) provide vital ecosystem services that support crop productivity, by regulating climate, protecting soils, conserving water resources, and improving the health, safety and livelihoods of rural communities in a variety of ways. Strategically integrating forests and trees into farming systems and landscapes can strengthen the resilience of food production in the

face of climate change while reducing environmental degradation, thereby creating positive outcomes for people and nature.

Forests and trees influence climate through evapotranspiration, in other words, latent heat flux, as well as through surface roughness, cloud formation and moisture recycling. In the tropics and many temperate contexts, these non-carbon effects cool and stabilize local to regional climates and can help sustain downwind rainfall (Bonan, 2008; Duveiller, Hooker and Cescatti, 2018; Ellison, Pokorný and Wild, 2024; Seymour, Wolosin and Gray, 2022). These processes can buffer both crops and rural workers from heat stress and extremes, complementing mitigation benefits from carbon. For rural workers, heat stress is an acute and growing occupational hazard, which lowers labour capacity and raises illness and injury risks (WHO & WMO, 2025). Forests and trees can materially lower local heat load, whereas deforestation has been linked to measurable productivity losses in rural labour (Ellison, Pokorný and Wild, 2024; Masuda *et al*., 2021; Parsons *et al*., 2021; Wolff *et al*., 2018).

Forests and trees help regulate hydrological cycles by influencing the timing, distribution and availability of water resources. Forests intercept rainfall and reduce runoff, mitigating the risks of soil erosion and moderating peak flows, reducing downstream flooding, and thus helping safeguard agricultural land and infrastructure (Ellison, Pokorný and Wild, 2024; Ilstedt *et al*., 2016). Targeted interventions use the intricate root systems of trees to enhance soil permeability and moisture retention, which can improve growing conditions for crops and reduce the impacts of drought stress (Bargués Tobella *et al.*, 2020; Ilstedt *et al.*, 2016). Forest conservation and sustainable management are indispensable, therefore, for the water security and resilience of agricultural systems.

The contributions of forests and trees to soil health and fertility underpin agricultural productivity and ecosystem stability. Through the process of litter decomposition, trees replenish soil organic matter and nutrient stocks, which fosters soil fertility and encourages microbial diversity (Kooch *et al.*, 2017; Muchane *et al*., 2020; Pardon *et al*., 2017). The dense root networks of trees anchor soil particles, thereby mitigating erosion and helping maintain soil structure (Yang *et al*., 2023). Forested landscapes harbour a diverse array of pollinators and natural enemies of pests, which enhances biological pest control and reduces the need for synthetic agrochemicals (Dainese *et al.*, 2019; Garibaldi *et al*., 2013).

Forests and trees can also provide a myriad of benefits that directly support agricultural livelihoods and well-being (Lawrence and Vandecar, 2015). By providing shade and shelter for livestock, supplying fodder and woodfuel for household consumption, and other contributions, forests and trees are invaluable assets in many agriculture-dependent communities. Forests also support income diversification and improving food and nutrition security, typically through the sale and consumption of non-timber forest products (Ickowitz *et al.*, 2022).

Recognizing this potential complementarity invites us to move beyond a narrow conservation-versus-production debate towards the design of policies and practices at multiple scales that harness the synergies between healthy forests and sustainable agriculture.

To drive more holistic and sustainable landscape management, it is necessary to explicitly and strategically account for these benefits, while also acknowledging the complex and locally specific nature of these benefits, as well as inherent forest–agriculture trade-offs (Reed *et al.*, 2017).

This report brings together the latest scientific findings on the benefits of forests and trees for agricultural resilience and productivity. It comprises a comprehensive review of relevant literature and case studies to provide decision makers with a robust synthesis of the evidence base on which to formulate policies and strategies for sustainable landscapes. Mapping the known benefits of forests and trees for agriculture and identifying knowledge gaps can help guide policy interventions and future

research efforts aimed at fostering synergies between agriculture and forests in a rapidly changing world.

Translating this knowledge into decision-making is challenging, in part, because these benefits are generally context- and scale-specific, and depend on a variety of factors, including the type of vegetation and agricultural practice in question, the scale at which these benefits are considered, the non-linear relationships between different benefits being provided, the types of crops being cultivated, and the objectives of the community and farmers themselves. Scale plays a multidimensional role in influencing these processes. These effects manifest differently depending on the location of interest (e.g. tropical, temperate, boreal), the size of the forested area, the distance between agriculture and forests (within the agricultural area, in the vicinity, or farther away), the type of vegetation (natural forests, planted forests, trees in savannahs), as well as the patterns of land-use management (agroforestry practices; forested areas present in fragmented patches, in large conservation areas, or scattered across the landscape).

This report highlights and contextualizes the benefits that forests and trees provide for more resilient, productive and sustainable food systems, thereby supporting the long-term prosperity of farmers and communities while safeguarding the ecosystems on which they depend. By considering all levels of context that influence the benefits of forests and trees, this report offers an evidence-based synthesis and interpretive guide. We synthesize and organize findings, indicate where the weight of evidence is strong, where it is mixed or context-dependent, and where gaps persist. The aim is to provide a clear map of mechanisms, outcomes and trade-offs that helps policymakers, practitioners and researchers locate relevant studies and adapt strategies to local conditions.

SCOPE AND RATIONALE

The focus of the report is on the climate and ecosystem service benefits provided by forests and trees for agriculture. Although acknowledging that the benefits extend beyond agricultural contexts, the analysis centres on how they directly affect agricultural outcomes. While there are many other ways in which forests and trees can provide benefits for agriculture, this report will focus on the role of forests and trees in:

a) Regulating climate at multiple scales.
b) Regulating water availability at multiple scales.
c) Impacting the productivity and resilience of crops and rural workers.
d) Supporting pollination, and soil and pest management.

For the purposes of the report, agriculture primarily focuses on crop cultivation, thus excluding livestock management and fisheries. The examination of benefits is framed around improving worker health and productivity, enhancing crop yields, and encouraging more sustainable and resilient agricultural practices.

Organizing evidence on forests, trees and agriculture is a daunting task, in large part due to the numerous benefits, mechanisms and contexts that can be explored, and due to the interconnected nature of these processes. Rather than pretend these processes can be cleanly separated, we have chosen a structure that addresses each topic at a time, while acknowledging the overlaps between them.

First, we address climate at global, regional and local scales. Global and continental benefits often play out far from where the forest change happens and are normally analysed using large-scale models. These benefits are important to consider in international and national policy processes. Local and subnational effects are felt on farms and in districts: temperature, wind and humidity shifts are shaped by both the density of forests and trees and by the way they are placed in the landscape. These processes are usually documented by field studies and high-resolution analyses and can inform practical choices by farmer and basin managers. Splitting the discussion allows for highlighting the

evidence that matches the scale of decision-making, without losing sight of the links between scales.

Then, water is given its own chapter. Water use is where climate meets day-to-day farming: how much is available, when it arrives, how clean it is, and how it moves through soils and streams. Farmers and basin managers make decisions about storage, allocation and quality with their own tools and timelines. While climate is a major driver, water management has distinct institutions and levers. Treating it separately makes the evidence and options easier to use and gives water the importance it requires.

We separate worker health from climate not because the topics are unrelated, but because workers are too often invisible in agricultural debates. Heat stress affects safety, productivity and well-being directly. Keeping this discussion in its own chapter ensures the evidence and practical measures are impossible to miss. It also signals that benefits for agriculture mean benefits to people, not just to crops.

Finally, we bundle biodiversity-mediated processes (pollination, natural pest control), soil functions (soil life, nutrient cycling) and other ecosystem service benefits (microclimate, and mulch, fodder and fuelwood provision) into a single chapter. These services tend to be managed together through habitat and practice choices on farms and across landscapes. Bringing them into one place avoids scattering similar studies and recommendations through the report. Where these services interact with climate and water (which they often do), we flag the connections and point back to the relevant sections.

Two important caveats. First, boundaries are practical, not absolute. You will see cross-references where chapters meet, and some references appear more than once because they illuminate more than one pathway. Second, this is not an inventory of every benefit that forests and trees provide for agriculture, but a thorough mapping of the benefits we set out to highlight.

REPORT STRUCTURE

Contextualizing the influence of forests and trees on agriculture

Chapter 2 provides essential context for understanding the relationship between forests, trees and agriculture. First, it contextualizes forest–agriculture interactions and explains the diverse ways in which forests and trees influence agricultural systems in different landscapes and at multiple scales. It also unpacks the biophysical, ecological and socioeconomic mechanisms through which these interactions occur. The chapter then introduces a resilience framework for agriculture. It defines what is meant by resilience in this context and explores how forests and trees can contribute to more adaptive, robust and sustainable food systems. This conceptual lens underpins the analysis in subsequent chapters.

Forests and trees for climate regulation

Chapter 3 explores the crucial role of forests and trees in regulating climate and, therefore, in enhancing agricultural productivity. This chapter presents case studies and research showing the positive impacts of forests on agricultural resilience, which are crucial for understanding regional climate dynamics and water availability. The chapter discusses the relationship between forests and climate change, and the impacts on agriculture from global to local scales.

Forests and trees in regulating the water cycle

Chapter 4 delves into the role of forests in regulating the water cycle and highlights how forests and trees serve as natural sponges that capture and store precipitation. The chapter also examines the contributions of forests and trees to maintaining water quality – another crucial service for sustainable agriculture.

Forests and trees for improving rural workers' health and productivity

Chapter 5 explores the ways in which forests safeguard the health and productivity of rural workers by mitigating heat-related health risks. The effects of extreme heat in human health and mortality are examined, along with the evidence for the role of forests in reducing heat stress in agricultural contexts.

Contributions of biodiversity-mediated and other ecosystem services for agriculture

Chapter 6 showcases the ecosystem regulating and provisioning services that forests and trees provide, including pollination, pest control, soil improvement, nutrient cycling, and fodder and fuelwood provision, which are vital for sustainable agricultural landscapes.

Pathways to foster forest–agriculture synergies

Chapter 7 concludes the report by summarizing its main key findings and illustrating pathways that can help decision makers foster forest–agriculture synergies.

Notes on terminology

In this report, forests and trees refer to "forests" and "trees outside forests", as defined by FAO and presented in **Box 1**. These then include:

- native woody ecosystems – covering closed and open forests, woodlands, woody savannahs, and shrublands; and
- trees in agricultural landscapes – such as trees in agroforestry systems, including field- and farm-boundary trees, live fences, windbreaks, and riparian buffers.

BOX 1

Relevant definitions around forests and trees

Forest: Land spanning more than 0.5 hectares with trees higher than 5 metres (m) and a canopy cover of more than 10 percent, or trees able to reach these thresholds *in situ*. It does not include land that is predominantly under agricultural or urban land use (FAO, 2023).

Trees outside forests: Trees growing in land uses not categorized as forest (e.g. other wooded land and other land with tree cover) (FAO, 2022).

Other wooded land: Land not classified as "forest", spanning more than 0.5 hectares; with trees higher than 5 m and a canopy cover of 5–10 percent, or trees able to reach these thresholds *in situ*; or with a combined cover of shrubs, bushes and trees above 10 percent. It does not include land that is predominantly under agricultural or urban land use (FAO, 2023).

Other land with tree cover: Land classified as "remaining land area", spanning more than 0.5 hectares with a canopy cover of more than 10 percent of trees able to reach a height of 5 m at maturity (FAO, 2023).

Planted forest: Forest predominantly composed of trees established through planting or deliberate seeding (FAO, 2023).

Plantation forest: Planted forest that is intensively managed and meets all the following criteria at planting and stand maturity: one or two species, even age class, and regular spacing (FAO, 2023).

Sources: See full box references at the end of the bibliography section.

Unless explicitly stated otherwise, our focus is on native trees and natural ecosystems. While many forest and agriculture interventions use non-native species, that is not the focus of this report. Forest plantations are excluded unless clearly indicated. Urban trees and strictly ornamental plantings are outside the scope, except where they are directly relevant to agricultural outcomes (e.g. peri-urban buffers). We recognize distinctions among primary, secondary and degraded forests, but do not disaggregate results by these condition classes unless explicitly stated.

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CHAPTER 2

Contextualizing the influence of forests and trees on agriculture

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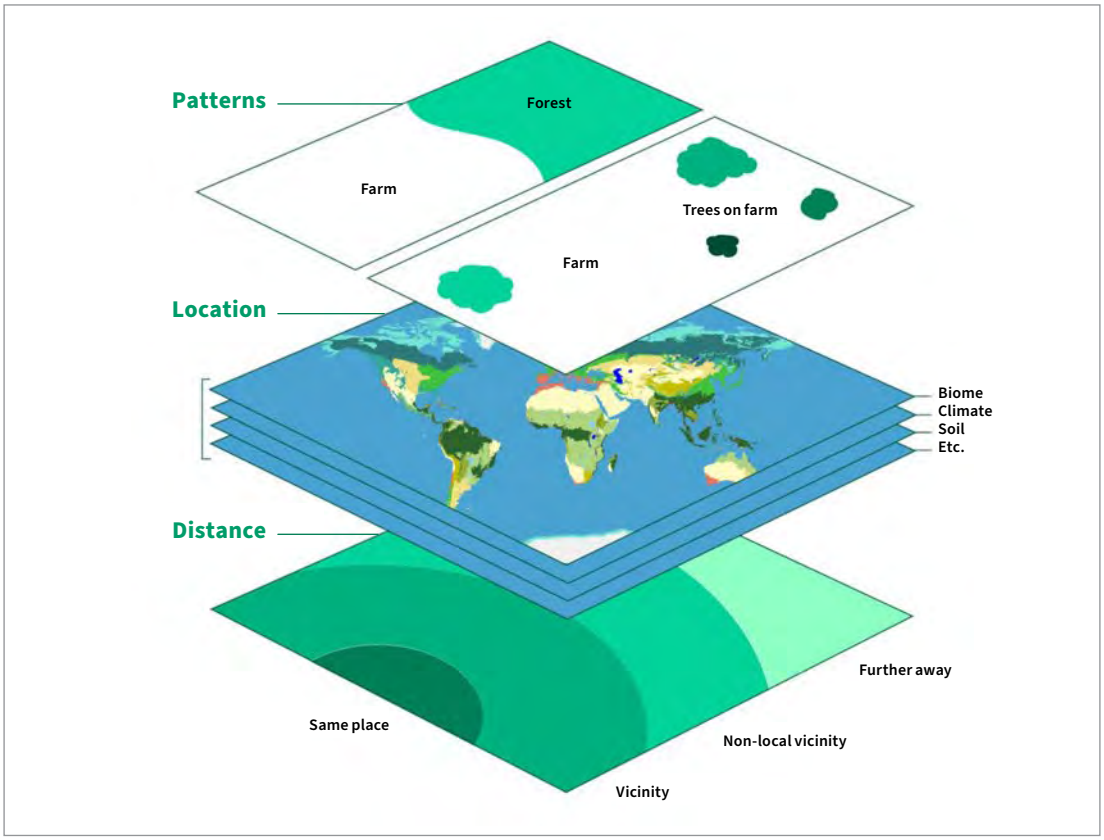
INTRODUCTION

To understand the ways in which forests and trees influence agriculture, it is necessary to contextualize their interactions. These interactions are not uniform across landscapes – they depend on the context in which they occur and specifically on three key aspects: (1) location; (2) distance; and (3) pattern (**Figure 1**).

Figure 1. *Factors that influence forest–agriculture relationships*



Location. Location determines crucial factors such as latitude, climate, soil type and topography, all of which affect the influence of forests and trees on agriculture. The geographic setting plays a central role in shaping the type, temporal variability and magnitude of forest–agriculture interactions. For example, the influence of forests on surface albedo – that is, the extent to which sunlight is reflected into the atmosphere – varies significantly between high-latitude temperate forests and low-latitude tropical forests.

Distance. The proximity of forests or individual trees to agricultural fields also matters. Trees that are integrated directly into agricultural systems have a more immediate and multifaceted impact on agriculture than forests and trees that are more distant from the agricultural setting. They may provide shade, influence local wind and temperature, and improve soil structure. More distant forests may influence agriculture in less direct ways, such as by regulating watershed dynamics and serving as upwind sources of precipitation. Thus, the spatial relationship between trees and farmland helps determine how benefits are distributed and perceived.

Pattern. The spatial pattern of trees and forests in agricultural landscapes, considering their density, distribution and fragmentation, is another essential dimension. A dense forest block has different ecological functions from a landscape in which the trees are scattered or in linear arrangements, such as windbreaks and riparian buffers. Moreover, trees dispersed throughout a farm may create a patchwork of incremental benefits, while trees along rivers might be more influential in stabilizing banks and regulating water quality. Fragmentation and connectivity also affect how wildlife, pests and beneficial species move across a landscape and thus influence the provision of ecosystem services crucial for agriculture.

In summary, a nuanced understanding of the relationship between forests, trees and agriculture must begin with a clear contextualization. Only by accounting for the specific characteristics of location, distance and pattern can we begin to accurately assess and enhance the ways in which these natural elements contribute to sustainable agricultural systems.

Besides these main biophysical factors that influence forest–agriculture relationships, other important factors include the type and age of trees, whether the vegetation is primary, secondary, or a plantation, and the biodiversity of the areas in question. These are vital factors that influence forest–agriculture relationships.

To better understand how forests, trees and agriculture interact, it is essential to recognize the multiple, context-dependent ways in which these interactions manifest across different landscapes. Although many combinations of location, pattern and distance between forests and agricultural areas are possible, certain main combinations emerge in real-world conditions due to economic, social and environmental factors. By examining these patterns, forest–agriculture systems can be categorized into types that reflect both spatial arrangement and functional relationships. This approach helps clarify how the proximity and placement of forests and trees in relation to agricultural areas influence ecosystem services, productivity and sustainability outcomes.

Table 1 presents six common typologies of forest–agriculture systems that capture this diversity: (1) proximate agroforestry; (2) boundary trees; (3) forest–agriculture interface; (4) mosaic landscapes; (5) regional forest–agriculture nexus; and (6) global forest–agriculture nexus. Each typology represents a distinct way in which forests and agricultural systems coexist and interact at different spatial scales. From individual farms that integrate trees directly into cropping systems, to global interdependencies shaped by land use, trade and ecological feedback, the categories offer a framework for analysing the complexity of forest–agriculture relationships and guiding land-use planning, policy and management strategies. Although agroforestry systems – in which trees are intentionally integrated with crops or animals, or both – are a crucial and widely recognized set of practices, they represent only part of the broader spectrum of forest–agriculture relationships.

Table 1. *Main typologies of forest–agriculture systems, and the scale in which they exist*

TYPE	SCALE	FOREST–AGRICULTURE SYSTEM	CHARACTERISTICS
1	Local	Proximate agroforestry	Tree crops and trees integrated into agriculture
2	Local	Boundary trees	Linear or marginal trees or forested areas within or around farms: windbreaks, trees planted along field edges, roads or riparian zones
3	Local	Forest–agriculture interface	Agricultural lands adjacent to large contiguous forest areas
4	Local/regional	Mosaic landscapes	A mix of forest patches and agricultural plots
5	Regional/ continental	Regional forest–agriculture nexus	Forest regions (e.g. protected areas) that can influence agricultural areas on a regional scale
6	Continental/global	Global forest–agriculture nexus	Larger forest regions that can influence agricultural areas on a global or continental scale (e.g. the Amazon biome, boreal forests)

MECHANISMS AND BENEFITS

Trees and forests influence agriculture through a series of connected effects, leading to broader environmental outcomes and tangible agricultural benefits. Different configurations of forest–agriculture systems (e.g. as enumerated in **Table 1**) determine which mechanisms are present or dominant in each landscape. These mechanisms interact and combine to produce system outcomes, such as local climate stabilization, soil moisture retention, erosion control, pollination services, and biological pest regulation. Together, these processes support key agricultural benefits, such as higher and more stable yields, improved working conditions, reduced input costs, lower climate risk and, ultimately, the greater sustainability and resilience of farming systems.

See **Box 2** for further details on biophysical, biogeochemical and biodiversity-mediated mechanisms.

The chain of effects shown in **Figure 2** and **Table 2** highlights that interventions at any point can have cascading impacts that propagate through mechanisms to influence outcomes in the agriculture sector. Recognizing this chain is essential for designing landscape-scale strategies that maximize synergies, and balance potential trade-offs.

In concrete terms, the chain of influence presented in the literature on this topic normally follows the order described hereafter.

Forests and trees, in particular their gain, loss, fragmentation and distance to agricultural areas, lead to system outcomes, which lead to agricultural outcomes. Except when it comes to agroforestry systems, forests and agriculture are two distinct systems. However, the effects of forests on agriculture depend on the configuration of both in relation to each other. For this reason, instead of considering only the distance, fragmentation and presence of forests and trees, we consider here forest–agriculture relationships more broadly as the main driver of benefits. Forest–agriculture systems themselves vary in configuration and scale, from individual trees, agroforestry systems and forest–agriculture interfaces, to mosaic landscapes, to the global forest–agriculture nexus. The type, density and spatial or temporal arrangement of tree cover in agricultural landscapes strongly determine the mechanisms that are active and the magnitude of their effects. This organization of concepts allows us to better understand the multiple pathways through which forests and trees sustain and enhance agricultural systems. The typology also helps identify leverage points for management interventions, such as integrating agroforestry, conserving forest edges and maintaining landscape heterogeneity, to optimize the provision of ecosystem services for agriculture.

Figure 2. *Chain of mechanisms and outcomes connecting forest–agriculture systems and benefits for agriculture*

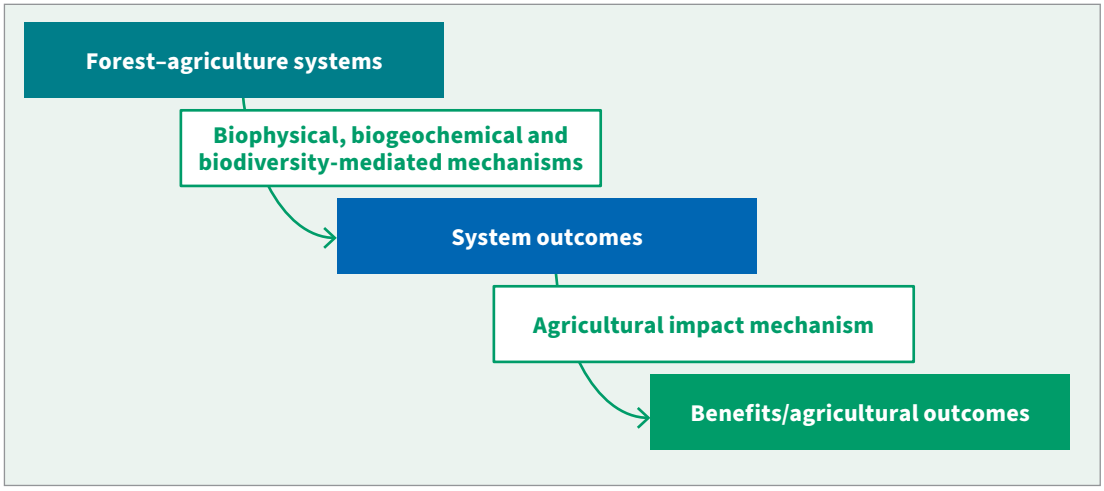


Table 2. *Broad description of drivers, mechanisms and outcomes in forest–agriculture relationships*

LINK IN THE CHAIN OF MECHANISMS	DESCRIPTION
Forest–agriculture systems	Trees on farms Agroforestry Boundary trees Forest–agriculture interface Mosaic landscapes Regional forest–agriculture nexus Global forest–agriculture nexus
System mechanisms (biophysical, biogeochemical and biodiversity-mediated processes)	Climate, hydrology and biodiversity-mediated mechanisms
System outcomes	Regulation of climate patterns and intensity of climatic events Regulation of water availability and fluxes of water Regulation of biodiversity and nutrient cycling
Agricultural impact mechanism	Effect of heat on rural workers Effect of water resources availability on crop productivity and resilience Effect of climate regulation on crop productivity and resilience Effect of improved soil conditions, increased pollination and biocontrol on crop productivity and resilience
Benefits/agricultural outcomes	Crop productivity Rural worker health and productivity Rural resilience and sustainability Prosperous livelihoods

BOX 2

Biophysical, biogeochemical and biodiversity-mediated processes

Biophysical mechanisms

Mechanisms that involve changes in energy, wind and water movement – the physics of the system. Examples: albedo (surface reflectivity), surface roughness (wind/turbulence), evapotranspiration, canopy shading, rainfall interception/throughfall, windbreak effects, soil-evaporation control, hydraulic redistribution (Bonan, 2008; Ellison *et al.*, 2017; Crockford and Richardson, 2000; Neumann and Cardon, 2012).

Biogeochemical mechanisms

Mechanisms that involve changes in carbon and nutrient stocks and flows, plus related atmospheric chemistry. Examples: carbon storage and sequestration, nitrogen fixation, litterfall and decomposition (building soil organic matter), deep root nutrient uplift, emissions of biogenic volatile organic compounds (BVOCs) that affect aerosols and clouds (Pan *et al.*, 2011; Cleveland *et al.*, 1999; Sayer, 2006; Paasonen *et al.*, 2013).

Biodiversity-mediated (ecological) mechanisms

Mechanisms that involve organisms and their interactions. Examples: habitat for pollinators and natural enemies (biocontrol), floral/resin resources, mycorrhizal symbioses, soil-fauna bioturbation that improves structure and infiltration (Garibaldi *et al.*, 2013; Letourneau *et al.*, 2011; Smith and Read, 2008; Lavelle *et al.*, 2006).

Sources: See full box references at the end of the bibliography section.

The mechanisms that connect forest–agriculture systems to system outcomes can be organized into three broad types of mediation: (1) climate; (2) hydrology; and (3) biodiversity. Within these mediation types, it is useful to distinguish specific mechanisms – that is, measurable biophysical processes performed by forests and trees – from emergent mechanisms that arise from the interaction of multiple specific mechanisms at the system scale.

Table 3 organizes these relationships according to the three mediation types:

1. **Climate mediation** refers to the ways in which forests and trees alter energy, moisture and gas fluxes and thus affect local to regional climatic conditions. Specific mechanisms include biophysical mechanisms, such as albedo modification, evapotranspiration and surface roughness, and biogeochemical mechanisms, such as carbon storage and sequestration, and emissions of aerosols and biogenic volatile organic compounds (BVOCs). These can contribute to outcomes like microclimate regulation and temperature moderation, which in turn generate agricultural benefits in the form of reduced heat stress on rural workers and crops, greater yield stability under climate variability, lower irrigation demand, and others.
2. **Hydrology mediation** involves processes that regulate water movement, availability and quality. Specific forest- and tree-related mechanisms like rainfall interception, hydraulic redistribution, soil evaporation, litter and organic matter decomposition, production of mulch, and deep root nutrient uptake influence emergent mechanisms, such as

soil water retention, runoff moderation and erosion control. These support agriculture by, for example, increasing drought resilience, reducing erosion losses, and providing a more sustainable water supply for crops.

3. **Biodiversity mediation** encompasses the role of forests and trees in maintaining and enhancing biological processes and organisms that support agriculture. Specific mechanisms include nitrogen fixation, deep root nutrient uptake, mycorrhizal associations, and habitat provisioning for beneficial species like pollinators and pest predators. Outcomes such as nutrient cycling, pollination services and biological pest control deliver benefits, such as increased yields, reduced input costs and enhanced food security.

These mediation types are highly interconnected. For example, shading and evapotranspiration (climate mechanisms) simultaneously affect soil moisture (hydrology) and microclimate conditions that support soil organisms (biodiversity). Similarly, litterfall improves both nutrient cycling and soil water retention.

Table 3. *System mechanisms, system outcomes and agricultural outcomes*

MEDIATION TYPE	SYSTEM MECHANISMS (biophysical, biogeochemical and biodiversity-mediated processes)	SYSTEM OUTCOMES	BENEFITS (agricultural outcomes)
Climate	Albedo Carbon storage and sequestration Surface roughness Emissions of aerosols and biogenic organic volatile compounds (BVOCs) Evapotranspiration Canopy shading Energy partitioning (sensible versus latent heat flux)	Local/regional temperature moderation Cloud formation Microclimate regulation Climate risk reduction	Increased crop yield stability under climate variability Reduced heat stress for crops Reduced irrigation needs Improved working conditions and lower heat stress for rural workers Sustainability and resilience of systems
Hydrology	Evapotranspiration Rainfall interception (canopy, litter) Throughfall and stemflow Hydraulic redistribution Deep water uptake Soil-evaporation control (shading, litter) Stem water storage	Soil water retention Runoff moderation Flood peak attenuation Groundwater recharge Soil erosion control Improved water balance and availability Water-quality regulation	Reduced erosion losses Improved soil moisture for crops Enhanced drought resilience Reduced irrigation costs Sustainability of water supply for agriculture Resilience to extreme rainfall events
Biodiversity	Nitrogen fixation Deep root nutrient uptake Litterfall and organic matter decomposition Mycorrhizal associations Bioturbation (soil fauna) Habitat provisioning (for pollinators, biocontrol agents) Resin/floral resources Root reinforcement (soil structure) Shade for understorey crops Windbreak effects Leaf fodder production Litter production for mulch Pruning/pollarding for woodfuel	Nutrient cycling Nutrient mobilization Soil fertility improvement Enhanced soil structure Pollination services Biological pest control Forage/fodder provisioning Mulching effects Woodfuel availability Forest edge effects (e.g. enhanced decomposition, nutrient gradients)	Increased crop yields Reduced fertilizer costs Enhanced soil fertility Pest damage reduction Maintained pollinator-dependent yields Livestock productivity gains Income diversification Household energy security Food security (quality and quantity) Sustainable, resilient farm systems

Downstream of these biophysical mechanisms, agriculture is affected through distinct impact pathways. Shifts in system outcomes such as temperature, humidity and water balance alter outcomes such as crop growth, phenology, input efficiency, yield stability, and rural labour supply, health and productivity. There is a rich literature in agricultural economics, agronomy and related fields documenting these pathways – using panel and experimental studies, process-based and statistical crop models, and remote sensing analyses. Together, these mechanisms underpin agricultural benefits from forests and trees that can contribute to productivity, resilience, sustainability and food security.

Among the many interactions that can be explored, each chapter of this report focuses on a specific slice of this chain of impact. **Table 4** describes the scope of each chapter, considering which forest–agriculture systems, mechanisms and outcomes they focus on.

Table 4. *Chain of drivers, mechanisms and benefits presented in each chapter of this report*

CHAPTERS	CHAPTER 3	CHAPTER 4	CHAPTER 5	CHAPTER 6
Chapter focus	• Forests and trees for climate regulation	• Forests and trees in regulating the water cycle	• Forests and trees for workers' health and productivity	• Biodiversity-mediated and other auxiliary forest ecosystem services and their contributions to proximate agriculture
Forest–agriculture systems	• Trees on farms/ agroforestry • Boundary trees • Forest–agriculture interface • Mosaic landscapes • Regional forest–agriculture nexus • Global forest–agriculture nexus	• Trees on farms/ agroforestry • Boundary trees • Forest–agriculture interface • Mosaic landscapes	• Forest–agriculture interface	• Trees on farms/ agroforestry • Boundary trees • Forest–agriculture interface
Mechanisms	• Climate-related mechanisms	• Climate- and hydrology-related mechanisms	• Climate-related mechanisms	• Biodiversity-mediated, soil functioning and ecosystem provisioning mechanisms
System outcomes	• Changes in climate patterns and intensity of climatic events	• Changes in water availability and quality and fluxes of water	• Changes in extreme heat and moisture at the local scale	• Changes in biodiversity and nutrient cycling
Agricultural impact mechanism	• Relationship between productivity and resilience of crops and climate	• Relationship between crop productivity and resilience and water resources availability and quality	• Effects of extreme heat on rural workers' health and well-being	• Relationship between nutrient cycling, biocontrol, pollination, and others, and crop productivity and resilience
Benefits/ agricultural outcomes	• Higher crop productivity • Rural resilience and sustainability • Prosperous livelihoods	• Higher crop productivity • Rural resilience and sustainability • Prosperous livelihoods	• Rural worker health and productivity • Rural resilience and sustainability • Prosperous livelihoods	• Higher crop productivity • Rural resilience and sustainability • Prosperous livelihoods

TRADE-OFFS AND ADVERSE OUTCOMES

The relationship between forests, trees and agriculture is complex and involves both benefits and trade-offs (Luedeling *et al.*, 2016). While forests can provide a wealth of ecosystem services that benefit agriculture, including climate and water regulation, biodiversity conservation, nutrient cycling and soil regeneration, there are also several trade-offs inherent within these systems that should be considered within sustainable landscape management planning.

The most glaring example of a trade-off is competition for land. As global demand for food and bioenergy increases, so too does pressure to expand croplands and pastures, often at the expense of forests, particularly in regions with fertile soils (Kopittke *et al.*, 2019). Additionally, as fertile lands become scarce, especially in areas with established infrastructure, marginal lands are often deforested (Spera *et al.*, 2014) and then abandoned due to their lower agricultural suitability and higher crop failure rates (Rattis *et al.*, 2021).

The expansion of agricultural land has contributed to deforestation (Pendrill *et al.*, 2022), but this relationship can also work in the opposite direction with expansion of forest land displacing agriculture. While this has been of considerably lesser concern, it should be considered within the current global focus on forest and landscape restoration and tree planting efforts, particularly in contexts where externally driven reforestation might compromise local food security. Likewise, policies that restrict agricultural expansion, for example through the establishment of forest protected areas, can also threaten food security and inhibit access to natural resources and forest provisioning ecosystem services, such as non-timber forest products (Castro and Kuntz, 2022).

Forests and trees can also pose disservices to nearby agricultural activities (Zhang *et al.*, 2017). Many of these are predation-mediated: forests may harbour predators and pests that threaten livestock and crops or serve as reservoirs for diseases that can

affect both animals and humans. Harmful organisms can include insects, snails, birds, mammals, fungi, bacteria, viruses and weeds (Tschumi *et al*., 2018). Several species of animals can provide benefits such as the control of both animal and plant pests, thus contributing to higher agricultural production; some, however, can also act as crop pests (Tschumi *et al*., 2018). These and other trade-offs need to be considered in their specific contexts because the balance between benefits and disservices can vary greatly. Other trade-offs include competition for water, nutrients and even pollinators. In some cases, dense forest cover can limit solar radiation, which may reduce crop yields in adjacent fields. Conflicting management objectives may also require trade-offs, such as forest protection versus production uses. Legal and economic conflicts may arise over land tenure, conservation policies, and the prioritization of forest protection over food production.

Balancing such trade-offs requires integrated land-use planning that considers the economic and ecological values of forests and the sociocultural dimensions of agricultural communities. With integrated strategies, it is possible to navigate these trade-offs and design landscapes in which forests and agriculture can coexist more sustainably. Understanding the trade-offs is crucial for evaluating the net benefits of forest–agriculture systems.

The benefits and trade-offs of forest–agriculture systems vary across climates, soils, crops and farming practices. This means that effective strategies must be tailored to local conditions.

At the same time, many benefits like water regulation and climate moderation extend beyond where they are generated. These cross-scale effects call for landscape-level planning and coordination across jurisdictions to ensure benefits are shared and trade-offs are managed.

Forest–agriculture interactions are context-dependent; therefore, the types of benefits available and the practices needed to enhance them are not universally transferable. Local biophysical and socioeconomic conditions will shape outcomes, necessitating context-specific assessments and tailored management strategies. Many ecosystem services from forests flow across spatial and temporal scales. For example, services such as moisture supply generated in one forest location may benefit agriculture in a distant location (such as through atmospheric moisture transport). These cross-scale dynamics highlight the importance of coordinated governance, landscape-scale planning, and institutional cooperation across jurisdictions to align incentives, manage trade-offs and distribute benefits equitably. Recognizing both the local specificity and broader spatial externalities of interactions is crucial for maximizing co-benefits and minimizing conflicts in forest–agriculture systems.

THE ROLE OF FORESTS IN AGRICULTURAL RESILIENCE

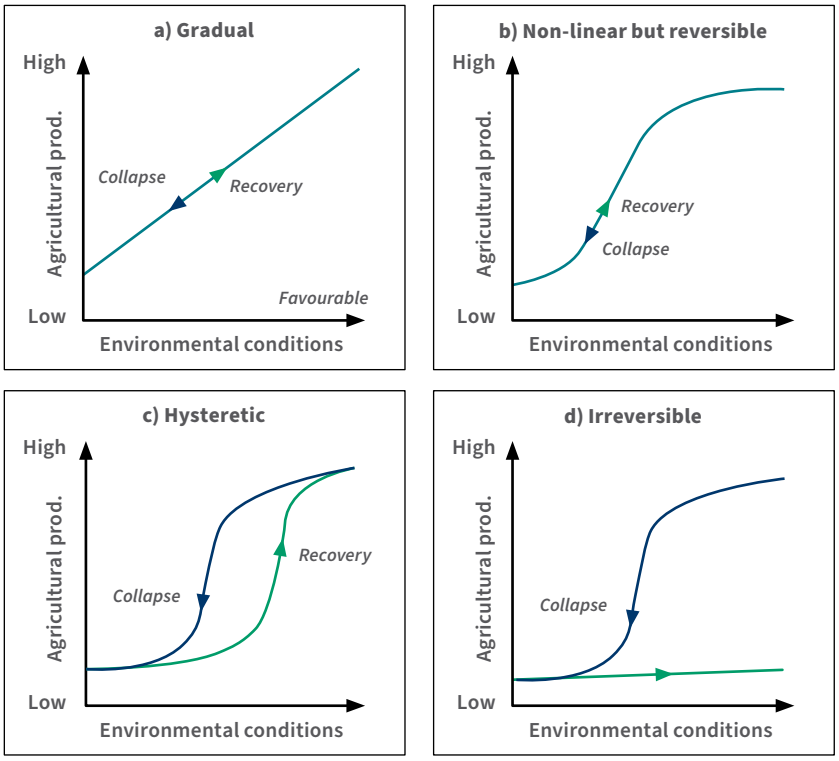
Forests and trees provide multiple benefits for agriculture, including regulating climate, supplying water, maintaining biodiversity and promoting worker health. In addition to enhancing agricultural productivity directly, these benefits help increase the resilience of agricultural systems – that is, their capacity to maintain structural and functional integrity through persistence, adaptation or transformation (Folke, 2006). Forests and trees increase agricultural resilience by reducing the occurrence and characteristics of shocks and creeping changes in environmental conditions and by increasing the socioecological capacity of agricultural systems to persist, adapt and transform. Increasing the resilience of agricultural systems is important given that they are increasingly exposed to climatic, ecological and socioeconomic shocks and changing environmental conditions.

Agriculture is one of the most sensitive sectors to climatic shocks, with the value of global crop production losses due to droughts and heat waves in the period 1961–2014 estimated at USD 237 billion (Mehrabi and Ramankutty, 2017). Some 20–40 percent of crop yields globally are lost annually to pests and diseases, causing substantial economic losses, increasing price volatility and threatening food security (IPPC Secretariat, 2021; Oerke, 2006; Savary *et al.*, 2019). An estimated 75–80 percent of croplands globally lack irrigation infrastructure, meaning that those areas rely exclusively on precipitation. This makes them highly vulnerable to variability outside expected precipitation and temperatures (Mehta *et al.*, 2024; Nagaraj *et al.*, 2021; Portmann, Siebert and Döll, 2010).

Irrigation systems are unevenly distributed. Although more than half the past century's irrigation expansion occurred in regions already experiencing water stress (Mehta *et al.*, 2024), 90–95 percent of agricultural areas in South America and sub-Saharan Africa still rely on rain as the only water source. Thus, many regions with the greatest exposure to hydroclimatic[1] extremes, the most pronounced adaptation gaps, and the highest demand for irrigation also have the highest economic and social vulnerability.

In resilient agricultural systems, external shocks are absorbed without causing persistent alterations to the system's fundamental structure and functions, which are vital for sustained agricultural production and the livelihoods of

Figure 3. *Overview of different types of change under changing environmental conditions*



Note: Changes in agricultural production, for example, can be (a) gradual and linear, where changes in environmental conditions are proportionately affecting agricultural production; (b) non-linear, where a gradual change in environmental conditions can result in an abrupt change in agricultural production; (c) hysteretic, where a non-linear change in agricultural production cannot easily be reversed, and the state of the agricultural production is dependent on the historical levels of environmental conditions; and (d) irreversible, where a non-linear change in agricultural production cannot be reversed within the foreseeable future or the timescale under consideration.

Source: Adapted from: Gordon, L.J., Peterson, G.D. & Bennett, E.M. 2008. Agricultural modifications of hydrological flows create ecological surprises. *Trends in Ecology & Evolution*, 23(4): 211–219. https://doi.org/10.1016/j.tree.2007.11.011

[1] Hydroclimate is the scientific field that brings together hydrology and climate, including the impacts that water and its processes have on the Earth's climate, and the impacts of climate patterns and change on the global hydrological (or water) cycle (NOAA and NWS, 2025). Hydroclimatic extremes refer to droughts, floods and extreme precipitation, extremely wet conditions and heat waves, among others (Li *et al.*, 2023).

agricultural communities. Recent observations indicate, however, that creeping changes in both climate and ecological conditions are eroding the resilience of both agricultural systems and their supporting forest systems, resulting in gradual, abrupt, hysteretic or irreversible shifts in these systems (**Figure 3**). In systems with low resilience, shocks are more likely to have significant impacts and to more easily trigger system transitions across thresholds towards different states. Examples of shifts in agricultural systems include desertification (Berdugo *et al.*, 2020; Burrell, Evans and De Kauwe, 2020); salinization (Shokri, Hassani and Sahimi, 2024); the collapse of pollinator-dependent crops (Latty and Dakos, 2019); groundwater and surface-water depletion (such as in the Aral Sea; Micklin, 2007); and socioeconomic triggers that lead to farm abandonment (Tindale *et al.*, 2024).

Forests and trees support agricultural resilience by moderating the characteristics of climatic, hydrological and ecological conditions through local-, regional- and global-scale processes. At the local scale, the high rates of forest evaporation contribute to lower surface temperatures and a lower risk of heat-induced productivity loss. Trees with deep roots can take up water from deeper soil layers to shallower ones that are easier for crops to access through hydraulic lift. At the catchment scale, forests can mitigate floods and reduce the risk of waterlogging on agricultural land by retaining rainwater and facilitating infiltration and percolation and the recharge of both surface and subsurface storage. This, in turn, helps reduce peak surface runoff and replenish water storage for irrigation. At the regional scale, water evaporated from forests can contribute to precipitation over agricultural areas, particularly in regions experiencing dry spells; in this way, forests play a regulating role in mitigating the severity and length of such dry spells and can also reduce variability in precipitation patterns. At the global scale, forests serve as an important carbon sink, essential for global climate stability, while maintaining biosphere integrity within a safe zone for human development.

Forests and trees also support agricultural resilience by enhancing the capacity of agricultural systems to withstand and absorb perturbations and to adapt or transform to retain their essential structures and functions. Forests and trees can help absorb hydroclimatic extremes such as droughts and floods. For example, trees next to agricultural areas can serve as barriers to soil erosion and minimize crop damage caused by strong winds; in agroforestry systems, trees provide shade that mitigates heat stress in crops. For communities experiencing crop failures, forests can function as a reserve, offering essential alternative sources of food, produce and income that contribute to diversified livelihoods and increased resilience. Moreover, forests and trees enhance the general adaptive and transformative capacity of agricultural systems. For example, healthy agricultural systems depend on forests for regulating pests and diseases, providing habitats for pollinators, ensuring nutrient cycling, protecting against soil erosion, and ensuring nitrogen fixation by bacteria in their carbon-rich soils. Outdoor rural workers who experience reduced heat stress and farmers facing diminished economic and psychological burdens from crop failures have greater resilience to cope, such as greater financial and social capacity to learn, innovate and collaborate.

The close interconnections between forests and agriculture mean that the loss of resilience in forests will have repercussions for agricultural resilience. For example, the expansion of agriculture into the Amazon rainforest has been shown to be a counterproductive process that diminishes rainfall and reduces crop yields (Leite-Filho *et al.*, 2021; Oliveira *et al.*, 2013). The resilience of forests is also threatened by climate change and forest degradation and deforestation (Singh *et al.*, 2024). Self-reinforcing feedbacks due to increasingly dry conditions and continued forest loss could push forest systems in the Amazon and other regions across thresholds towards treeless savannah-like states (Flores *et al.*, 2024; Zemp *et al.*, 2017).

Other factors, such as biodiversity, also play crucial roles in forest resilience. For example, degraded forests have been found to absorb substantially less carbon than healthy forests (Zuidema and Jakovac, 2023), and forests with lower biodiversity are more vulnerable to drought, wildfire and pest outbreaks (Klapwijk and Björkman, 2018).

The resilience benefits of forests and trees depend on the context. In some situations, the presence of woody vegetation can lead to shocks and detrimental changes in environmental conditions or adversely affect the adaptive or transformative capacity of interconnected agricultural systems. Semi-natural woody landscapes can harbour agricultural pests (Bartual *et al*., 2019), and plantations can reduce streamflows and contribute to water scarcity (Buechel, Slater and Dadson, 2022; Hoek van Dijke *et al*., 2022). The shade that trees provide in agroforestry systems can be a disadvantage because the reduced radiation can lower crop productivity (Luedeling *et al*., 2016). Furthermore, forestry programmes that are implemented with the minimal involvement of local communities are unlikely to generate sustained local benefits and may even adversely affect the social adaptive capacity of the communities (Lee and Krasny, 2017).

Effective resilience management practices involve the integration of three key elements: (1) local knowledge; (2) community involvement; and (3) biodiversity conservation. In the Plurinational State of Bolivia, for example, the successful adoption of biodiverse agroforestry in cocoa plantations – which has been shown to enhance resilience to climate impacts – was facilitated by knowledge sharing through social organizations and cooperatives (Jacobi *et al*., 2015). More generically, the array of approaches for enhancing resilience can be summarized as seven core principles (see **Box 3**): (1) maintain diversity and redundancy; (2) manage connectivity; (3) monitor slow variables and feedbacks; (4) understand systems as complex adaptive systems; (5) encourage learning and experimentation; (6) broaden participation; and (7) promote polycentric governance systems (Biggs *et al*., 2012). These principles, although applicable broadly across systems, are interdependent and context-specific. Given the numerous cross-scale connections between forests and agriculture, the application of these principles requires integrated approaches that consider forests and agriculture as unified systems.

Forests enhance agricultural resilience in two crucial ways: (1) by limiting the occurrence of hydroclimatic extremes and reducing ecological risks, and preventing the associated shocks from being transmitted to the agricultural system; and (2) by increasing the internal biophysical and social resilience of agricultural systems in absorbing perturbations and adapting and transforming. Forest resilience is threatened by climate change and deforestation, which have negative knock-on effects on agriculture. Given the substantial pressure on forests stemming from the agriculture sector, it is crucial to mitigate adverse impacts and to adopt practices that proactively integrate forests to strengthen the resilience of interconnected forest–agriculture systems. Moreover, weather extremes and pressures on ecosystems are intensifying in regions where communities are often least resilient to climate change and have contributed least to greenhouse-gas emissions. Enhancing agricultural resilience through forest resilience requires a comprehensive systems approach across multiple temporal and spatial scales. This underscores the urgent need for the collective assumption of responsibility, encompassing bilateral and multilateral commitments, to strengthen global resilience and sustainability.

BOX 3

The seven resilience principles

Maintaining diversity and redundancy (P1): Diversity encompasses the various elements and features within the system that exhibit varying responses to disturbances (e.g. species richness). Redundancy refers to alternative elements and features serving the same function within the system, capable of substituting for one another when disruptions or perturbations occur (e.g. availability of different water resources).

Managing connectivity (P2): Connectivity describes the manner and extent to which resources, species or social actors disperse, migrate or interact across ecological and social landscapes (e.g. connectivity between habitats).

Managing slow variables and feedback (P3): Slow variables determine the underlying structure of the system, evolving gradually over time. However, if these variables surpass a specific threshold, they can induce a significant regime shift within the system. Feedback occurs when a change in a particular variable or process amplifies or dampens subsequent changes of a similar nature within the system. Therefore, the meticulous monitoring of these variables and feedback mechanisms is essential. Ecosystem services, such as clean water, air quality, nutrient cycling, tourism and recreation, exemplify this principle.

Fostering complex adaptive systems thinking (P4): This principle posits that enhancing resilience necessitates an integrative and holistic management approach that accommodates various spatial and temporal scales along with associated uncertainties. Such management processes prioritize adaptive management of the system in the face of uncertainty, disturbances and shocks rather than attempting to eliminate them. For example, existing forest management programmes, when considered alongside the geopolitical significance of the area and assessments of vegetation cover, can yield a more comprehensive strategy for enhancing resilience.

Encouraging learning and experimentation (P5): The dynamic nature of systems and their inherent uncertainties necessitate the continuous updating of knowledge through experimentation and systematic monitoring. This iterative learning process equips stakeholders to adapt effectively to changes and bolsters their capacity to respond to future challenges. Facilitating information exchange among key stakeholders serves as a means to evaluate this principle.

Broadening participation (P6): This principle posits that enhancing resilience requires a decision-making process that actively involves key stakeholders and incorporates their perspectives, thereby evaluating their interests in collaboration to augment the sustainability of the system. The community-based forest management initiatives that give local communities co-management rights over forest regions, such as those in the Amazon region of Brazil, are an example of this principle (de Andrade, Sacomano Neto and Candido, 2022).

Polycentric governance (P7): Polycentricity refers to a governance system characterized by multiple decision-making centres operating at various scales, integrating multiple levels of authority, and facilitating coordination among local, regional and national stakeholders. Decentralized forest governance models, such as Indonesia's community forestry programmes, exemplify the efficacy of this approach. In these programmes, local villages manage forest areas under government oversight, guided by clear protocols for responsibilities and resource sharing among different governance levels. By encouraging collaborations among many stakeholders, collaborative decision-making networks further strengthen polycentric governance (Ahmadi *et al.*, 2019). For instance, in Costa Rica, private landowners, government organizations and conservation non-governmental organizations (NGOs) collaborate to create reforestation policies through multistakeholder forums (Wallbott and Florian-Rivero, 2018).

Sources: Adapted from Biggs *et al.* (2012). See full box references at the end of the bibliography section.

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CHAPTER 3

Forest–climate–agriculture interactions at multiple scales

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KEY MESSAGES

- **Forests regulate climate** by moderating temperatures, sustaining precipitation and reducing the impacts of droughts, thereby directly supporting agricultural productivity and resilience.
- Evidence from Brazil shows that **the conversion of tropical forests to farmland reduces evapotranspiration** by about 30 percent, causing local temperature increases and negatively impacting rainfed agriculture.
- Global evidence shows that **agricultural areas in 155 countries rely on forests** in other countries for up to 40 percent of annual precipitation, underscoring the transboundary nature of forest–climate–agriculture interactions.
- **Promoting forest–agriculture synergies requires integrated land-use strategies** that recognize local agricultural priorities and the climate benefits provided by forests.

INTRODUCTION

The world's forests play crucial roles in regulating climate at multiple scales. They provide agricultural systems with a wide range of benefits, from regulating the Earth's surface heat budget, to maintaining and supporting continental precipitation patterns, to providing biophysical habitats for key agriculturally beneficial species. Forests, therefore, are critically important for current and future food production. Deforestation and increasing concentrations of greenhouse gases in the atmosphere, however, are altering these dynamics and changing how the benefits derived

from forests flow to agricultural systems. This chapter explores these topics at multiple scales, focusing on a set of benefits that forest–climate interactions provide for agriculture and how these might plausibly change under global climate change. Understanding the interactions between forests, climate and agriculture requires an examination of processes at global, continental, regional and local scales, because the drivers, feedbacks and effective interventions differ profoundly across these scales. At the global and continental scales, forest–climate–agriculture dynamics are shaped by broad forces such as greenhouse-gas emissions and large-scale land-use change, which drive shifts in atmospheric circulation, rainfall patterns and climate regimes. In contrast, local and regional dynamics are influenced more directly by specific biophysical conditions, such as soil type, vegetation composition and microclimate, as well as by local governance systems, cultural practices and livelihood strategies. These differences mean that the actors, motivations and leverage points for managing forest–climate–agriculture interactions vary significantly depending on scale and that solutions that are effective at one level may be ineffective or even counterproductive at another.

There is a fundamental contrast in the kinds of evidence available at global versus local scales, which influence both scientific understanding and policy design. Global analyses rely heavily on models and remote sensing; they may offer broad patterns but often lack the resolution needed to capture fine-scale variability and social contexts. Local studies, in contrast, can measure specific mechanisms and outcomes *in situ*, which enables researchers to contrast large-scale models with ground-level data. Local interventions such as agroforestry and community-managed riparian buffers typically address immediate, context-specific needs, and global interventions like REDD+, carbon markets and large-scale reforestation programmes target broader climate and biodiversity goals. Bridging these differences in scale, evidence and tools is crucial for ensuring that policies are scientifically grounded, context-sensitive and effective, both locally and globally.

MECHANISMS

Overview

The world's forests and trees are powerful forces in shaping climate at all scales. Forest losses and gains affect climate via biophysical and biogeochemical pathways, as described in **Box 4**.

Forest–climate interactions (the green boxes in **Figure 4**) provide numerous benefits (shown in the

BOX 4

Summary of biogeochemical and biophysical pathways covered in this chapter

Biogeochemical

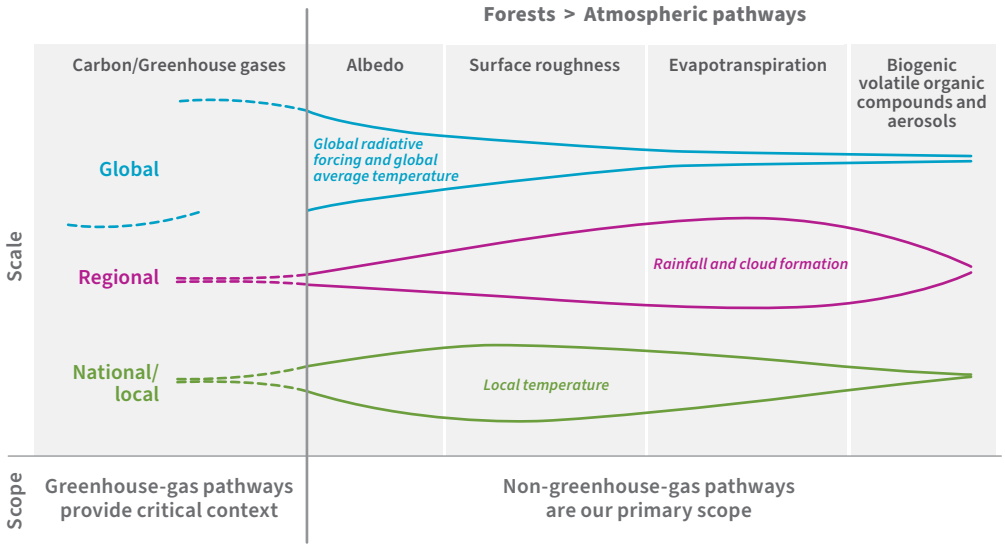
Biogeochemical pathways involve the **exchange of greenhouse gases** (GHGs) such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) between the land surface and the atmosphere. Forests absorb CO_2 through photosynthesis and store it in biomass and soils. With forest loss, carbon stored in the vegetation and soil is emitted to the atmosphere. The consequent increased concentration of atmospheric greenhouse gases contributes to global warming.

Biophysical

Biophysical pathways involve the exchange of **energy, water and momentum (e.g. movement of air masses) between the land surface and the atmosphere**. They affect climate directly through physical processes. The biophysical pathways include mechanisms such as albedo, evaporation and surface roughness, and biogenic volatile organic compounds (BVOCs).

Different forest–climate mechanisms will have different impacts on climate at different scales (**Figure A**). Some will have a direct influence on local climate: for example, tropical deforestation affects the local radiative balance by disrupting the albedo–evapotranspiration system, which has immediate consequences for local land surface temperatures (Silvério *et al.*, 2015). Other mechanisms will have impacts at the scale of entire countries or even continents – for example, evapotranspiration in the Amazon rainforest is a source of moisture for large areas of South America (Bottino *et al.*, 2024; Sheil, 2018).

Figure A. *Importance of the different mechanisms at multiple scales*

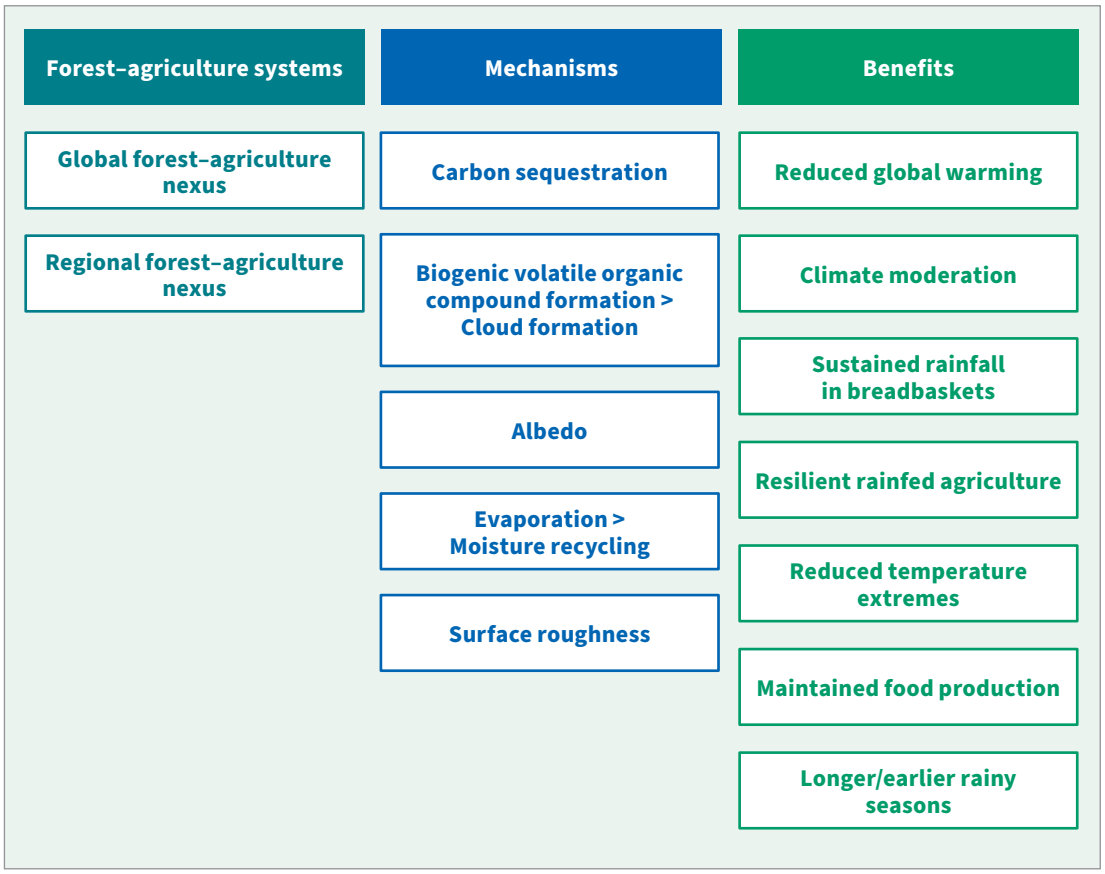


Note: At the global scale, greenhouse gases have the greatest impact on global temperature and net radiative budgets, followed by surface albedo. At the regional scale, evapotranspiration and biogenic volatile organic compounds are relevant to rainfall patterns and cloud formation. At the local scale, albedo, canopy roughness and evapotranspiration are important drivers of temperature.

Source: Seymour, F., Wolosin, M. & Gray, E. 2022. *Not Just Carbon: Capturing All the Benefits of Forests for Stabilizing the Climate from Local to Global Scales.* https://doi.org/10.46830/wrirpt.19.00004

Sources: See full box references at the end of the bibliography section.

Figure 4. *Summary of the forest–agriculture systems, mechanisms and benefits addressed in the chapter*



white boxes), from large-scale climate stabilization to localized improvements in agricultural conditions, particularly with respect to temperature and precipitation. **Figure 4** and **Table 5** show the main mechanisms discussed in this chapter and the main benefits of these.[2]

Forest–climate mechanisms

Carbon dynamics. Changes in local carbon dynamics can significantly affect climate, and, conversely, climate variations can affect carbon stocks. For example, shifts in water availability, wind speed, air temperature and humidity influence the frequency and severity of wildfires, which cause the rapid release of carbon stored in vegetation. Strong storms can also lead to large-scale tree mortality (windthrows), thus exposing previously stored carbon to decay and release to the atmosphere. Additionally, changes in seasonal temperature patterns can have cascading effects. A warmer winter and spring, as observed in the Northern Hemisphere in 2006–2007, can trigger early leafing and flowering and thereby make crops more vulnerable to late frosts. Such interactions between climate and the carbon cycle are difficult to predict because of limitations in the detail of atmospheric models, and understanding of ecosystem responses at differing timescales is incomplete (Heimann and Reichstein, 2008).

At more localized scales, warming accelerates soil carbon turnover, especially in Arctic tundra and boreal soils, where faster decomposition releases large carbon stores previously constrained by cold temperatures (Ren *et al.*, 2024); tropical forest soils are similarly affected but to a lesser extent. These local changes are compounded by disturbances such as increased wildfire frequency and permafrost thaw, which further weaken carbon storage capacity.

[2] Wintertime forest–climate benefits are not discussed here because they are beyond the scope of the chapter. Agriculture is generally not practised when soils are cold, and precipitation falls as snow.

Such regional and local shifts are examples of climate feedbacks: self-reinforcing changes in the Earth's temperature due to secondary effects. Some feedbacks, however, such as CO_2 fertilization, can promote vegetation growth and carbon uptake, although increased soil carbon release may offset these gains (Hausfather *et al.*, 2020). Dynamic vegetation responses to changing climate conditions will also influence the carbon cycle at the regional to local levels, introducing additional uncertainty into carbon-sink projections (Hausfather *et al.*, 2020).

Canopy roughness, which is related to the structure and irregularity of forest canopies, directly affects the fluxes of water vapour and sensible heat by influencing wind currents. Canopy roughness creates turbulent eddies, which have an important effect on the vertical mixing of air masses across the land–atmosphere boundary (Maurer *et al.*, 2013; Thomas and Foken, 2007). As a result, heat and water vapour are transported to higher altitudes and do not accumulate near the surface. The water vapour condenses quickly in the atmosphere, and the heat is released at high altitudes, as opposed to near the surface (Lawrence *et al.*, 2022).

The turbulence caused by the multilayered, multispecies canopy structures of natural forests mixes the air, increases evapotranspiration and decreases local temperatures (Lawrence *et al.*, 2022). Deforestation reduces this effect – even when the new land use comprises forest-like plantations, which have more homogeneous canopy structures with a lower air-mixing effect and fewer associated positive effects on evapotranspiration and local temperatures (Fayad *et al.*, 2021; Pfeifer *et al.*, 2018). Roughness plays a larger role in regulating local temperature in tropical forests than in temperate forests, although the effect in the latter is still strong (Lawrence *et al.*, 2022) .

Evapotranspiration. Evapotranspiration is the sum of plant transpiration and water evaporation from the soil surface; it accounts for approximately 60 percent of total land precipitation. Transpiration is the major component of evapotranspiration in tropical forests, contributing an average of 70 percent of the total.

Forest trees have deep roots and therefore high capacity to move water from the soil to the atmosphere via transpiration. The process also affects temperature because the conversion of liquid water into vapour carries energy as latent heat, which does not raise the local temperature. Latent heat released by evapotranspiration can remove more than 50 percent of the surface energy input from solar radiation, thus reducing local temperatures (Liu *et al.*, 2021; Oki and Kanae, 2006). Because trees with deep roots support sustained transpiration, even in dry periods, their presence maintains this cooling effect consistently. This process not only lowers the temperature but also increases atmospheric humidity. Those two effects can benefit crop growth by reducing heat and water stress, influencing both the immediate surroundings and the local landscape. The cooling under tree canopies can create more favourable microclimates for agriculture, especially during heat waves (Dobhal *et al.*, 2024). Agroforestry, including shelterbelts, can enhance crop resilience to increased temperatures and drought conditions caused by climate change by providing natural cooling and improved water regulation. This can reduce heat stress on crops and improve yields, making transpiration and tree cover crucial for sustainable agriculture under global warming.

Forest evapotranspiration varies seasonally, and there is a latitudinal gradient. In the tropics, evapotranspiration has low seasonal variance because of consistent rainfall and energy availability, with large volumes of water returned to the atmosphere year-round (Vourlitis *et al.*, 2015). Evapotranspiration rates in temperate forests are approximately five times higher in spring and summer than in winter, which causes a threefold decrease in sensible heat, even with higher radiation rates (Wilson and Baldocchi, 2000). Evapotranspiration falls considerably in winter, but the net effect on temperature is not drastic because of the concomitant reduction in solar radiation.

In winter, therefore, temperate forests may have mild local heating effects (Schultz, Lawrence and Lee, 2017; Wilson and Baldocchi, 2000). The net result of such interannual variability is a latitudinal gradient in the effects of temperate forests on local climates, with multiple studies indicating that the tipping latitude (i.e. the latitude at which the effect of forests changes from net cooling to net warming) is 35–50° north (Lawrence *et al.*, 2022).

The conversion of forests to croplands and pastures has a direct impact on water and energy fluxes and, consequently, on evapotranspiration. Evidence from Brazil shows that the conversion of forests to rainfed agriculture leads to reductions of approximately 30 percent in evapotranspiration (Silvério *et al.*, 2015), which is reflected in increases in local temperatures (Prevedello *et al.*, 2019). The reductions are even steeper in the dry season because evapotranspiration rates fall fivefold in the non-growing seasons of crops but remain relatively constant in tropical forests (Maeda *et al.*, 2021; Suyker and Verma, 2009). This warming can lead to a hotter microclimate that stresses rainfed crops and reduces their productivity (Prevedello *et al.*, 2019). Additionally, the decrease in evapotranspiration reduces atmospheric moisture and rainfall recycling, potentially leading to drier soils and less water availability for agriculture in the long term. This can exacerbate drought conditions, with negative impacts on crop yields and increased irrigation needs.

Albedo. Albedo is a physical property related to the surface capacity to reflect or absorb solar radiation. Snow and ice – which have high albedo – are important components of global climate regulation because they reflect up to 90 percent of incoming radiation; they are also highly affected by climate change (Hall, 2004). At the other end of the spectrum, forests have very low albedo; they absorb more radiation than any other type of land cover. Moreover, the higher net radiation absorbed by forests is an important factor in stimulating convection, which leads to increased precipitation over forested regions (Bonan, 2008; Lawrence and Vandecar, 2015; Leite-Filho *et al.*, 2021).

The highest difference in albedo between forests and other land cover is in boreal regions due to the presence of snow and ice for large periods of the year, which increases the reflection of solar radiation. This causes boreal forests to retain energy, especially in winter months when the area of snow and ice is greatest (Schultz, Lawrence and Lee, 2017). Thus, boreal forests play important roles as local climate stabilizers; their removal would cause an increase in temperature during warm seasons and in daytime through loss of evaporative cooling and a decrease in temperature in winter and at nighttime from albedo effects (Lawrence *et al.*, 2022). Temperature fluctuations and the associated increase in thermal stress represent significant threats to agricultural productivity because higher temperatures during critical growth periods can reduce grain yields and compromise crop performance (Lobell and Gourdji, 2012).

The impacts of albedo on local temperatures are related intrinsically to forest evapotranspiration. Deforestation increases albedo, which increases the amount of radiation reflected and reduces the amount of energy absorbed. The net result of deforestation, therefore, should be local cooling due to increased albedo. This balance is affected, however, by the simultaneous reduction of evapotranspiration, which in tropical forests is so high that it more than offsets the local cooling effects of albedo due to deforestation and leads to increased local temperatures (Abera *et al.*, 2019). Because evapotranspiration is lower in temperate and boreal regions, deforestation causes local cooling at latitudes above 35° north (Lee *et al.*, 2011). Similarly, in subtropical regions such as southern Brazil, where evapotranspiration is also relatively low, the increase in albedo following deforestation is not counteracted by latent heat fluxes, resulting in a net cooling effect. In contrast, in tropical regions such as the Amazon, the loss of forest cover significantly reduces evapotranspiration, disrupting the latent heat flux and intensifying local warming, even in the presence of increased albedo.

Climate change has a strong impact on the snow–albedo feedback in the Northern Hemisphere. Climate warming will reduce snow cover and expose surfaces with lower albedo; this will cause the higher absorption of solar radiation and increase local temperatures further (Thackeray and Fletcher, 2016). Areas that have lost their snow cover are 2.8 °C warmer, on average, and an increase of 1 °C further reduces snow extent by 1 percent (Kaufmann and Pretis, 2023).

Aerosol emissions. Forests release BVOCs, which influence secondary organic aerosols (SOAs) and play important roles in biogeochemical and biophysical processes. The overall temperature

effect of BVOCs is mixed because they have multiple effects, some of which warm and others cool the climate. Large afforestation projects, such as those in China, have provided evidence of an increase in BVOC emissions, specifically isoprene (Wang *et al.*, 2021).

Reactive compounds like ozone, hydroxyl radicals, and nitrates readily oxidize BVOCs in a complex set of reactions that can affect the lifetime of atmospheric methane and increase its concentrations as well. In the presence of reactive nitrogen oxides, oxidation of BVOCs also promotes the formation of tropospheric ozone – a greenhouse gas that affects human and plant health, including crop health (Lobell, Di Tommaso and Burney, 2022). At the same time, BVOC oxidation produces SOAs, which reflect sunlight (a direct cooling effect) and serve as condensation nuclei for clouds, which can further cool the atmosphere (Rap *et al.*, 2013; Scott *et al.*, 2014, 2018).

Because BVOCs can both warm (through ozone and methane) and cool (through aerosols and clouds), their overall impact on climate is complex and uncertain. For agriculture, this dual effect adds further complexity. On one hand, BVOC-derived aerosols and clouds can cool local climates and may increase rainfall, potentially benefiting crop growth. On the other hand, ozone formed from BVOC reactions can damage leaves, reduce photosynthesis and lower crop yields. Biogenic volatile organic compounds and their oxidation products can also contribute to air pollution.

Ultimately, the net impact of BVOCs on climate and agriculture depends on the balance between their cooling (aerosol formation) and warming (ozone production) effects. This balance varies with environmental conditions, crop types, farming practices and atmospheric composition, making it difficult to precisely estimate how BVOCs shape local climates and crop performance (Peñuelas and Staudt, 2010; Scott *et al.*, 2018). However, the presence of forests appears to have a small cooling effect from BVOCs (Lawrence *et al.*, 2022).

Table 5. *Summary of the mechanisms and benefits of forest–climate interactions addressed in the chapter*

MECHANISM	HOW IT WORKS	BENEFITS FOR AGRICULTURE
Carbon sequestration	Higher uptake of atmospheric carbon dioxide (CO_2) by forest biomass and soils reduces greenhouse forcing over decades.	Mitigation of biogeochemical climate change trends and patterns.
Moisture recycling (forest–atmosphere)	Moisture generated by evapotranspiration in upwind forests drives large-scale rainfall downwind via moisture-transport corridors.	Provides more reliable precipitation, particularly for rainfed crops in agricultural basins downwind of forest areas.
Biogenic volatile organic compound-driven cloud formation	The emission of biogenic volatile organic compounds (BVOCs) by trees promotes aerosol nucleation and cloud condensation, enhancing cloud cover.	Higher cloud cover reduces daytime temperatures and ultraviolet exposure, lowering heat stress on sensitive crops. Higher cloud formation can also influence rainfall.
Albedo feedback (land-cover change)	The presence of forests and trees alters the quantity of energy reflected from the Earth's surface compared with lighter surfaces such as open land.	Regional changes in albedo can influence temperatures at different scales.
Large-scale wind and circulation effects	Forest structure modifies surface roughness (e.g. more trees tend to increase roughness), thus altering moisture and energy flows.	Stabilization of rainy-season onset and duration, which reduces the risk of crop failure later in the growing season.

GLOBAL TO CONTINENTAL FOREST–CLIMATE–AGRICULTURE INTERACTIONS

Temperature

Forests play an essential role in regulating the Earth's climate by influencing continental and global temperatures (Ellison, Pokorný and Wild, 2024). Land-based ecosystems remove up to 30 percent of human-generated carbon dioxide (CO_2) emissions from the atmosphere annually (Friedlingstein *et al.*, 2025). Forests are especially important because they store in their biomass, soils, dead wood and litter about 36 percent more carbon than oceans and (on average) twice as much carbon as non-forest ecosystems (Pan *et al.*, 2024). Of the forest types, tropical forests are most effective in capturing carbon, with sequestration rates 78 percent higher than those for temperate forests and more than double those for boreal forests (Pan *et al.*, 2024). Deforestation and forest degradation, however, have significantly reduced the carbon benefits of tropical forests (Pan *et al.*, 2024).

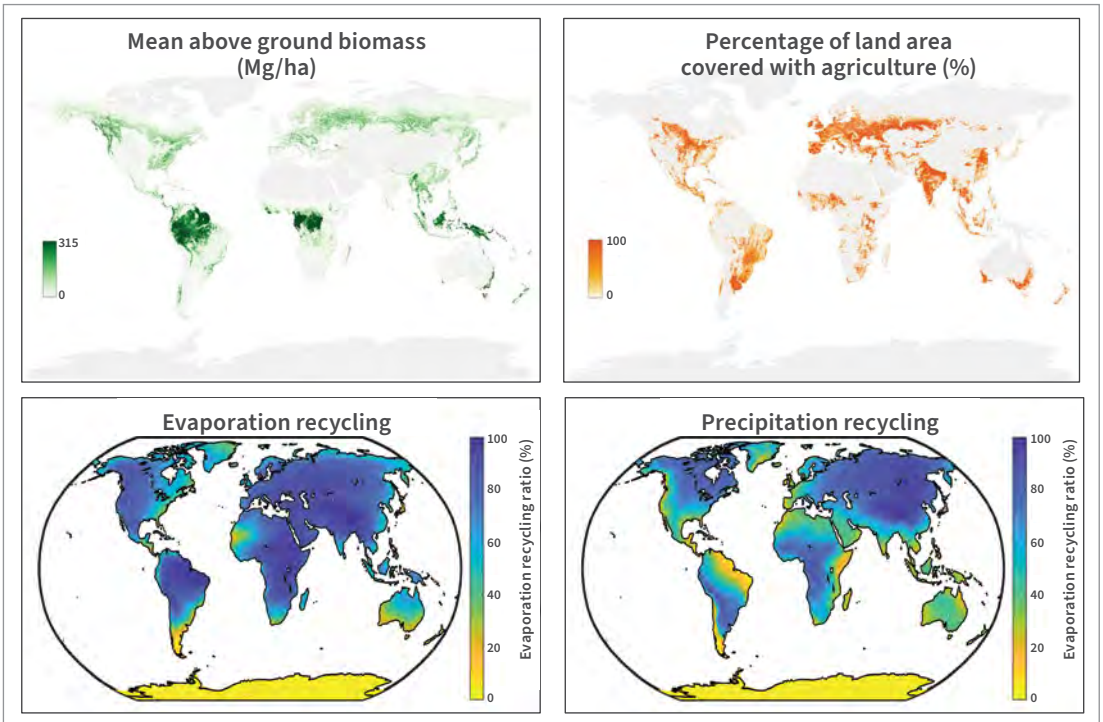
Earth system models – that is, large models used to better understand global climate and to generate climate change projections – are helping explore the biophysical and biogeochemical effects of changes in forest area globally. Recent modelling studies have estimated the global effects of large-scale land-use change on the climate, with a main focus on temperature (Winckler *et al.*, 2019; Boysen *et al.*, 2021). The most recent assessment using a collection of Earth system model outputs (Amali *et al.*, 2025) found that changes in the Earth's vegetation in 1985–2014 caused biophysical changes in temperature globally that were very different from changes in temperature due to greenhouse-gas emissions. Changes in land cover in temperate and boreal regions contributed to global cooling, and land-cover changes in tropical regions contributed to warming.

Rainfall regulation and global rainfed agriculture

A key benefit of forests for agriculture is the regulation and promotion of precipitation in a process known as precipitation or moisture recycling. Evaporation arising in forested areas travels through the atmosphere (either locally or to remote locations) and falls later as precipitation (Ellison, Futter and Bishop, 2012; Keys *et al.*, 2012; Van der Ent *et al.*, 2010). Certain parts of the world are disproportionately more reliant on moisture recycling originating in forests and thus are particularly vulnerable to deforestation, which could pose direct risks to food and water security (Keys *et al.*, 2022; Keys, Wang-Erlandsson and Gordon, 2016; Seymour, Wolosin and Gray, 2022). For example, the Congo River basin is highly reliant on moisture recycling, specifically evaporation arising in Central Africa and falling as precipitation elsewhere in the basin. The case study in **Box 5** on moisture recycling in the Congo illustrates this (Nyasulu *et al.*, 2024).

Deforestation reduces surface roughness, leading to increased wind speeds and reduced moisture convergence (Eiras-Barca *et al.*, 2020). Moisture is transported downwind of the deforested area, where eventually the moisture is precipitated out (Eiras-Barca *et al.*, 2020; Khanna *et al.*, 2017). An increase in the deforested area can create a dipole pattern

Figure 5. *From left to right and top to bottom, world maps showing above ground biomass, global cropland density, the continental evaporation recycling ratio and the continental precipitation ratio*



Notes: Refer to the disclaimer on page ii for the names and boundaries used in this map. Upper left: above ground biomass (Mg/ha), demonstrating the density of the world's forests; upper right: global cropland density (%); bottom left: continental evaporation recycling ratio – the share of evaporation from land that turns into precipitation in other land areas; bottom right: continental precipitation recycling ratio – the share of precipitation in an area that comes from moisture evaporated in other land areas. Precipitation recycling is the amount of rain that falls in a certain area that originates in another land area. The map on the right shows the amount of rain in absolute terms (mm) originating in other land areas, and the map on the left shows the percentage of rain that falls in a certain area that originates in other land areas.

Sources: Top maps created by the authors based on: Teluguntla, P., Thenkabail, P., Xiong, J., Gumma, M.K., Giri, C., Milesi, C., Ozdogan, M. *et al.* 2015. Global Cropland Area Database (GCAD) derived from Remote Sensing in Support of Food Security in the Twenty-first Century: Current Achievements and Future Possibilities. In: *Land resources: monitoring, modelling, and mapping.* Boca Raton, USA, Taylor & Francis. https://pubs.usgs.gov/publication/70117684; and Bourgoin, C., Verheggen, A., Carboni, S., Ameztoy, I., Ceccherini, G., Colditz, R. & Achard, F. 2020. Global Forest Monitoring: Global map of forest types 2020 – version 0. [Accessed on 21 October 2025]. https://forobs.jrc.ec.europa.eu/GFT#data_download

Bottom maps adapted from: Staal, A., Meijer, P., Nyasulu, M.K., Tuinenburg, O.A. & Dekker, S.C. 2025. Global terrestrial moisture recycling in Shared Socioeconomic Pathways. *Earth System Dynamics*, 16(1): 215–238. https://doi.org/10.5194/esd-16-215-2025

of cloud cover across the deforested area (Khanna *et al.*, 2017). In this phenomenon, upwind sections of the deforested area are dominated by horizontal moisture transport towards the downwind section, where lifting convection occurs (Khanna *et al.*, 2017).

Forest-sourced precipitation plays a vital role in maintaining the delicate balance of water and surface energy and thus ensuring a stable and reliable water supply for agriculture and other biosphere activities (Bruijnzeel, 2004). The deforestation of certain tropical forests, such as in the Amazon, has been linked to changes in precipitation, including the delayed onset of rainy seasons – crucial periods for rainwater-dependent agriculture – and shortening of their duration (Butt, de Oliveira and Costa, 2011; Costa and Pires, 2010). Under climate change, therefore, regions that are heavily reliant on forest-sourced precipitation are vulnerable to land-use and land-cover change and its impact on climatic variability and drought, compromising food production (Swann *et al.*, 2015).

Evidence obtained from tracking the sources and destinations of evaporation around the world suggests that around 70 percent of all terrestrial evaporation precipitates over land and that about 51 percent of global precipitation over land has evaporated from land (Tuinenburg, Theeuwen and Staal, 2020). Most terrestrial evaporation is in tropical forest areas, where high evaporation rates are caused by a combination of high temperatures and the large volume of biomass. A large proportion of the areas that depend on upwind forests for the regulation of precipitation patterns is situated in areas with rainfed agriculture.

Recent analysis of sources of moisture from forests that provide precipitation to global agricultural areas showed that agricultural areas in 155 countries rely on forests in other countries for up to 40 percent of annual precipitation, and that moisture from forests globally supports 18 percent of the crops those countries produce and 30 percent of the crops they export. This study also demonstrated that countries with extensive areas that are highly dependent on precipitation from forests, such as Argentina, Brazil, Canada, China, the Russian Federation, and Ukraine, are also major crop producers and exporters (Pranindita *et al.*, 2025).

Rainfed subsistence agriculture is an essential feature of global food security, and forests play a crucial role through evapotranspiration. In addition to increasing downwind rainfall quantity, forests help regulate rainfall variability by sustaining moisture in the atmosphere during droughts and other dry spells and by providing an ongoing flow of moisture for agricultural areas.

The timing of tropical precipitation can be substantially affected by deforestation; changes to planting windows could make certain cropping systems untenable in the future. This is particularly evident in South America, where the timing of the continental-scale South American monsoon system is dependent on exchanges of water and energy in the Amazon forest (Wright *et al.*, 2017). Deforestation effects, at scales ranging from local to continental, can delay and shorten rainy seasons in the Amazon and Cerrado regions (Commar, Abrahão and Costa, 2023). Deforestation at the scale of a few square kilometres in the Amazon can delay the onset of the rainy season by about one week on average but by up to one month in years in which large-scale conditions such as the El Niño–Southern Oscillation (ENSO) are already unfavourable for precipitation in the region (Leite-Filho, de Sousa Pontes and Costa, 2019).

Movement of water across continents

Forests serve as conduits for the atmospheric water cycle across continents, including Africa, Eurasia and North America. Forests, especially tropical rainforests, exert a significant influence on global and local precipitation patterns through evapotranspiration. The underlying parameters that define such forest–precipitation linkages are surface heat partitioning, especially the fraction of latent heat flux (i.e. moisture released via evapotranspiration); the contiguity of the forest ecosystem (i.e. how patchy it is); and the ecosystem's leaf area index (i.e the leaf area relative to the ground surface), with the corresponding moisture flux through stomata.

Impacts from observed disturbances

Among the forest types, the highest evapotranspiration rates are in evergreen broadleaf forests, with a mean estimate of 1 227 mm/year (Yang *et al.*, 2023), which is more than twice the average global estimate of 578 mm/year for croplands and 461 mm/year for grasslands (Yang *et al.*, 2023). Evapotranspiration in deciduous broadleaf forests, although not markedly high (678 mm/year, on average), also generally exceeds that of cultivated lands (Yang *et al.*, 2023).

Evapotranspiration rates in tropical humid forests are usually in the range of 3–4 mm/day; on average, they are 46–49 percent higher (on an annual scale) than those for cultivated lands (Maeda *et al.*, 2021; de Oliveira *et al.*, 2019; Paca *et al.*, 2019). There is high seasonal variability in the evapotranspiration differences between forests and cultivated lands, however, with strong contrasts in dry seasons and wet-to-dry transitional months – because the deep root systems of trees enables greater access to groundwater – and smaller differences in rainy seasons due to the non-limited availability of soil water (Maeda *et al.*, 2021; Paca *et al.*, 2019). Evidence suggests that a change from forest to non-forest (such as non-irrigated cropland and grazing land) could lead to a reduction in evaporation of more than 30 percent (Sterling, Ducharne and Polcher, 2013).

REGIONAL FOREST–CLIMATE–AGRICULTURE INTERACTIONS

The effects of forests on temperature go beyond their influence on local temperature. Temperature effects of deforestation have been observed some kilometres away from the deforested site. In the Amazon, for example, the impacts of deforestation have been observed up to 100 km away, with air temperature increasing by approximately 2 °C when 50 km^2 of forest were removed (Butt *et al.*, 2023; Cohn *et al.*, 2019). Similar results (albeit with different rates) were obtained for the cooling effect of tree cover in urban areas (Zhou *et al.*, 2015; Ziter *et al.*, 2019).

A possible cause of the regionally significant impacts of deforestation is the advective transport of sensible heat (Lawrence and Vandecar, 2015), but this is not straightforward. The results of simulations point in the opposite direction, with advective processes reinforcing the albedo-cooling effect of deforestation and transporting cool, dry air over large areas – in which case the regional effects of deforestation would have, overall, a cooling effect on global temperature (Winckler *et al.*, 2019). It is also possible that different regions will exhibit differing behaviours according to their particularities. For example, the high evapotranspiration rates in the Amazon rainforest mean that water vapour and

Table 6. *How different mechanisms interact at the local and regional levels historically and in future projections, for the world's main forest types*

		LOCAL	REGIONAL	EFFECTS ON AGRICULTURE
Tropical forests	Historical	Warming effects due to relatively low albedo are compensated by evapotranspiration and canopy roughness, resulting in a net cooling effect. Forests have a higher impact on local temperature in drier regions.	Variation in albedo due to forest loss decreases at latitudes below 50° N. The reduced cooling effect, combined with higher losses due to evapotranspiration, leads to regional warming. The higher production of biogenic volatile organic compounds (BVOCs) reduces incoming radiation and increases cloud formation.	High evapo-transpiration rates increase air moisture, reducing water stress, especially in the beginning of the wet season. Regulation of rain onset and predictability for crop calendar.
	Future	Increased carbon dioxide (CO_2) concentrations may lead to a higher frequency of stomata closing, which would reduce the cooling benefits of evapotranspiration. The combined effects of projected deforestation and climate change would lead to even greater local increases in temperature.	Deforestation in the tropics could amplify global climate change by disrupting precipitation patterns and increasing heat stress.	Higher water stress. Possible reduction of CO_2 uptake and photosynthetic rates.
Temperate forests	Historical	At high latitudes (30–56° N), forest cover results in a local net warming effect due to the lower impact of evapotranspiration and the difference between forest and snow albedo. Forests have a mixed effect at lower latitudes (below 30–56° N), with local net cooling effects in summer and warming effects in winter.	There is net warming at latitudes > 50° N because reductions in albedo offset the effects of greenhouse-gas (GHG) emissions and evapotranspiration.	Climate regulation, with higher temperatures in winter and cooler temperatures in summer.
	Future	Snow and ice feedbacks will weaken in future warmer climates, reducing the biophysical cooling effects of forest loss. Longer growing seasons and higher CO_2 concentrations may enhance forest productivity, which would slightly increase evapotranspiration effects, but this may not fully counteract the loss of albedo cooling at high latitudes.	Afforestation in temperate regions may provide regional cooling effects, but only in areas where the gains from evapotranspiration and cloud formation outweigh losses from surface albedo. At high latitudes, however, afforestation may still lead to net warming due to the loss of reflective snow cover.	Higher heat stress.
Boreal forests	Historical	Boreal forests contribute to net warming due to their low albedo, especially when replacing snow-covered landscapes.	Snow–albedo feedback is an important regulator of regional climates in the Northern Hemisphere.	
	Future	Climate change may lead to the northward expansion of boreal forests, further reducing albedo and amplifying local warming.	Climate change has a decisive impact on snow–albedo feedback by reducing snow cover and thereby reducing albedo and further increasing temperatures.	Possible extension of agriculture in boreal regions.

regulating precipitation are transported over large distances. This has an overall cooling effect but, in its absence, areas are projected to become drier and to experience greater temperature anomalies (Bottino *et al.*, 2024).

Boreal and temperate forests

Boreal and temperate forests are important for regulating temperature and precipitation in Asia, Europe and North America. The interplay between forest cover and climate regulation is crucial for maintaining agriculture-conducive conditions in these regions, particularly in terms of stabilizing local weather patterns and supporting moisture recycling.

The influence of forests on temperature in boreal areas is driven mostly by albedo. Trees are darker and reflect less energy than snow cover, and the presence of trees therefore contributes to an overall temperature increase. This warming effect is much less important in regions with little snow.

Another key mechanism in boreal and temperate areas is cloud formation. Fewer trees mean less cloud formation, which contributes to temperature increases. These two processes – albedo and cloud formation – occur simultaneously and partly balance each other. Even though evaporation is lower in boreal and temperate areas than in tropical regions, the contribution of moisture from boreal and temperate forests to downwind precipitation can be high, especially in eastern North America and central Eurasia (see **Figure 5**).

Tropical forests

Tropical and subtropical forests have a profound impact on agricultural systems at the local to regional scale. They influence climate by regulating temperatures and precipitation, and support biodiversity, which is crucial for agricultural productivity. In Southeast Asia, Central Africa and the Amazon, tropical forests provide agriculture with direct benefits through climate regulation (Seymour, Wolosin and Gray, 2022).

Tropical forests contribute to the mitigation of global warming beyond their capacity to store carbon. They influence temperature mainly through albedo and the emission of BVOCs, which increase cloud formation and consequently the reflection of energy through cloud albedo. Their high evapotranspiration rates, combined with their influence on surface roughness, albedo and cloud cover, affect the energy budget and climate patterns on a global scale. For example, deforestation of about 50 percent of tropical forest is estimated to increase land surface temperature by 1 °C, but the restoration of this deforested area would decrease land surface temperature by the same amount (Prevedello *et al.*, 2019).

Savannah forests

Field measurements in the savannahs of the central Rio Grande plains of southern Texas, United States of America, have shown that climatic fluctuations significantly influence the relative densities of woody plants and herbaceous vegetation (Rodriguez-Iturbe *et al.*, 1999). For example, woody plant coverage decreased in periods of severe drought between 1941 and 1960, while wetter conditions between 1961 and 1983 led to an increase in woody plant density from 8 percent to 36 percent. This dynamic interplay between vegetation and climate illustrates the sensitivity of savannah ecosystems to climatic variations and underscores the importance of maintaining vegetation cover to support soil moisture levels and mitigate the impacts of climate change.

LOCAL FOREST AND CLIMATE BENEFITS FOR AGRICULTURE

The mechanisms through which the regional climate effects of medium- to large-scale deforestation can affect local agriculture can be conceptualized as three interconnected processes. First, in the absence of snow-related effects (which usually do not occur during cropping seasons), deforestation leads to increases in local temperatures and makes daytime temperatures higher (Alkama and Cescatti, 2016). The direct effect of increased temperatures on crops is highly dependent on the nature of the crop

and background climate conditions (Lancaster and Humphreys, 2020); it can often be at least partially counteracted by simple adaptation measures, such as switching varieties (Pires *et al.*, 2016). Higher temperatures, especially higher maximum daily temperatures, can lead to more than linear increases in vapour pressure deficit (VPD; Lobell *et al.*, 2013; Rigden *et al.*, 2020; Schauberger *et al.*, 2017). Therefore, a substantial part of the impact of higher temperatures on crop yields is through its influence on water stress. As VPD increases, the air pulls more water from plants and soils; thus, crops and trees lose water faster, increasing their risk of heat stress and drought damage. Conversely, lower VPD means that the air is closer to saturation, and plants lose water more slowly. As VPD increases, many plants respond by closing their stomata to avoid water loss, which means reducing their uptake of CO_2 and rate of photosynthesis; higher VPD increases soil water loss and causes higher water stress in water-limited conditions.

The second and third processes relate to precipitation and its seasonality and are of particular importance in tropical regions. As discussed further in this chapter, tropical deforestation at scales larger than a few square kilometres reduces rainfall in the region (Smith, Baker and Spracklen, 2023). Due to several documented circulation processes related to water and energy transport, deforestation in one region can also affect precipitation in regions hundreds and even thousands of kilometres away. Although circulation processes can lead to slight increases in precipitation in parts of the region in response to deforestation, the net effect is almost always negative at scales ranging from municipalities to continents (Badger and Dirmeyer, 2016; Eltahir and Bras, 1994; Khanna *et al.*, 2017; Saad *et al.*, 2010). Because most tropical agriculture is water-limited – with the possible exception of excess rainfall at critical times for mechanized operations such as harvesting – lower rainfall leads to higher water stress and ultimately to lower crop yields.

Local management practices have important implications for crop production in mitigating harmful climatic conditions. Adopting proximate agroforestry systems, such as alley cropping, can result in significant increases for crop yield. In temperate regions, increases of 6–44 percent can be obtained when crops (e.g. maize, soybean, wheat and black bean) are grown near trees, due to protection from wind and better microclimatic conditions (Majaura, Böhm and Freese, 2024). Similar results have been found in other regions, with intercropping reducing air and soil temperatures by approximately 2 °C. Moreover, the retention of boundary trees and silvopastures is important for controlling soil erosion by reducing water runoff and wind erosion (de Aguiar *et al.*, 2010; Béliveau *et al.*, 2017).

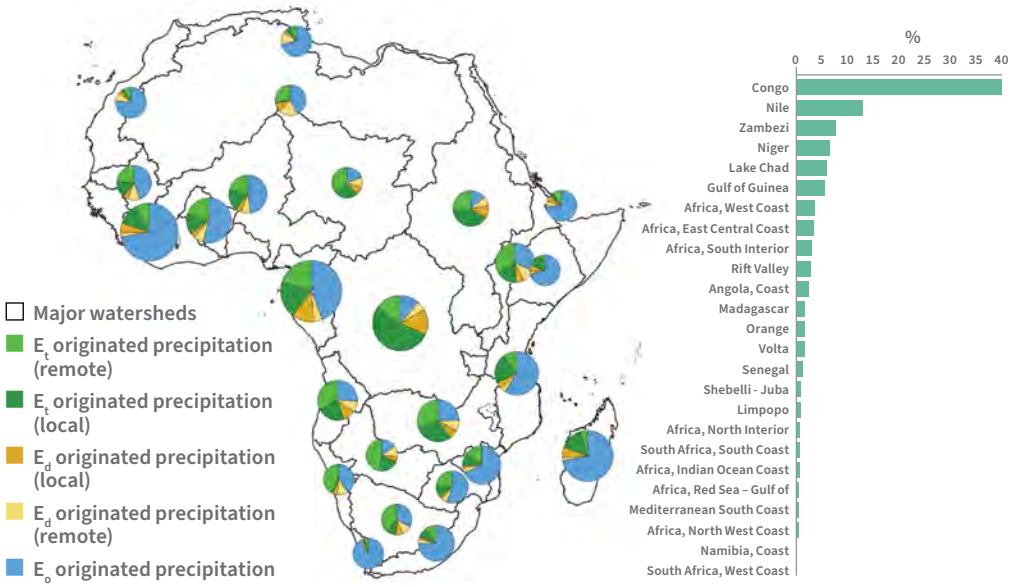
BOX 5

Congo basin agriculture and forest–climate interactions

The Congo basin, Central Africa's vast tropical rainforest, is critical for climate regulation, biodiversity and regional precipitation. Declining precipitation within the basin, linked to forest cover changes, underscores the urgent need for policy action to protect this vital ecosystem and support the livelihoods of the millions of people who depend on it.

Almost 50 percent of precipitation over the African continent derives from transpiration worldwide, with a disproportionate share originating in the Congo basin (**Figure B**).

Figure B. *Sources of mean annual precipitation over major African watersheds averaged over 1981–2016*



Notes: Refer to the disclaimer on page ii for the names and boundaries used in this map. (a) Shades of green represent vegetation-sourced precipitation (P) over the watershed; shades of yellow represent precipitation originated from direct evaporation from the soil surface, intercepted rainfall and open waterbodies (E_d). Blue represents the ocean-originated precipitation. The size of each pie-chart represents the magnitude of mean annual precipitation. (b) Contribution (%) of each watershed to the total continental precipitation sourced from the biological flux of transpiration (E_t).

Source: Te Wierik, S.A., Keune, J., Miralles, D.G., Gupta, J., Artzy-Randrup, Y.A., Gimeno, L., Nieto, R. & Cammeraat, L.H. 2022. The Contribution of Transpiration to Precipitation Over African Watersheds. *Water Resources Research*, 58(11): e2021WR031721. https://doi.org/10.1029/2021WR031721

Policy relevance

- ***Climate regulation:*** The Congo rainforest significantly influences global and regional climates through evapotranspiration, recycling over 40 percent of its moisture locally and contributing over 10 percent of precipitation to remote African agricultural areas. Deforestation threatens these services, potentially altering West African monsoon patterns, increasing Sahelian rainfall while decreasing rainfall along the Guinea coast, and raising basin temperatures by 2–4 °C.
- ***Food security:*** Forests provide essential wild foods and ecosystem services, sustaining local livelihoods and contributing to food security. Most local communities rely on subsistence, small-scale agriculture—the leading driver of forest change in the region, primarily through shifting

Continued on next page

cultivation systems (Shapiro *et al.*, 2023). These systems depend on the regeneration and ecosystem services of surrounding forests. The invisible linkages of moisture recycling are vital for green water availability in agriculture. In addition, indigenous cultures are deeply intertwined with the rainforest, valuing canopy cover for spiritual and traditional practices.

- ***Trade-offs:*** Forests offer economic benefits through wild foods, ecotourism and non-timber forest products, serving as a vital safety net while also providing carbon sequestration and climate regulation. Deforestation, however, leads to local soil degradation and biodiversity loss. On a global level, deforestation disrupts Earth system processes, such as the water cycle, which is evidenced by shorter fallow periods between agricultural planting seasons.

Recommendations

1. ***Strengthen policy implementation:*** Translate existing strategic instruments into on-the-ground action to promote forest conservation and sustainable agriculture.
2. ***Contextualize forest restoration:*** Ensure restoration efforts consider species diversity and hydroclimatic suitability for enhanced resilience. Advance moisture recycling science to enable targeted management actions in critical moisture source/sink hot spots.
3. ***Empower local actors:*** Support local land tenure rights, especially for women, to improve forest management, and address challenges to scaling these practices.
4. ***Strengthen regional frameworks:*** Leverage African Union initiatives like the Continental Green Recovery Action Plan (CGRAP), the Biodiversity Strategy and Action Plan (BSA), and Agenda 2063 to provide strategic direction for conservation and development in the region.
5. ***Foster global collaboration:*** Recognize the global importance of the Congo rainforest requiring collective national, regional and international support and incentives.

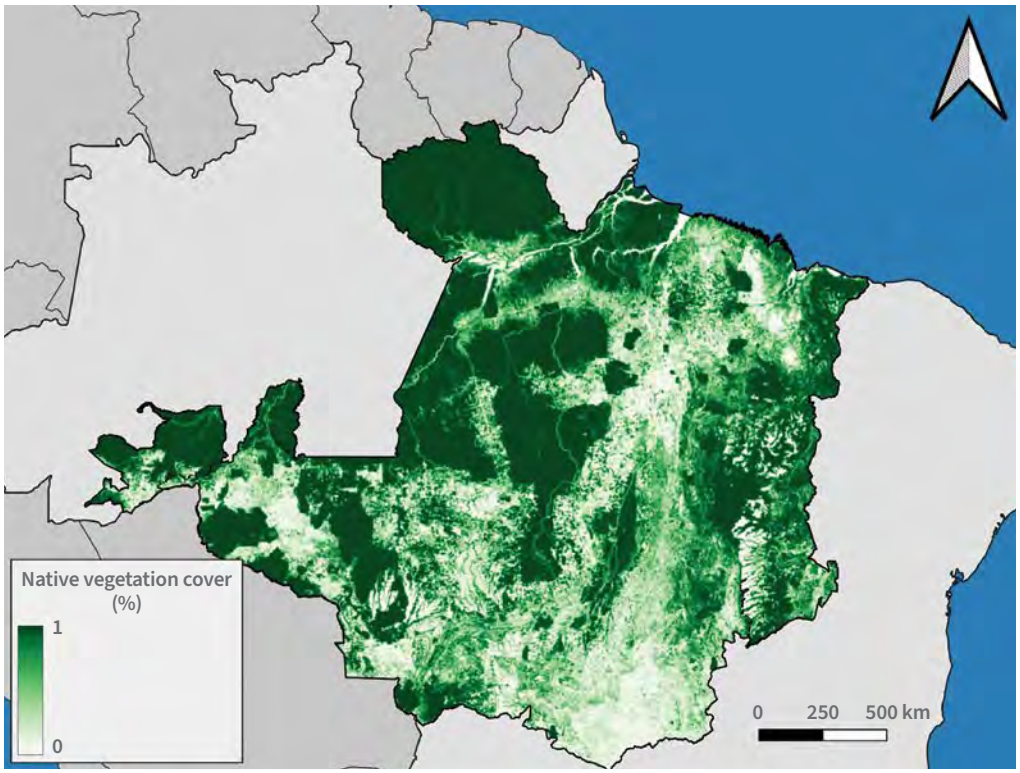
Note: Refer to the disclaimer on page ii for the names and boundaries used in this map.

BOX 6

The Brazilian Amazon-Cerrado region

The Amazon rainforest is the largest rainforest in the world and is critical for global climate regulation, with the water and carbon cycles playing important roles (Albert *et al.*, 2023). However, due to climate change and land-use change, the rainforest's role as one of the major terrestrial carbon sinks is under threat, and the forest is now emitting more carbon than it is absorbing (Gatti *et al.*, 2021). The Amazon-Cerrado region is one of the most important agricultural regions in the world, accounting for 25 percent of Brazilian agricultural production, with soy and maize important crops (IBGE, 2024). This represents a significant change from only 40 years ago, when over 85 percent of the area was covered by native vegetation. Since 1985, the region has lost 67 million hectares of forest cover, an area larger than France or Spain (MapBiomas, 2023).

Figure C. *Native vegetation cover in the Amazon-Cerrado region in 2021*



Note: Refer to the disclaimer on page ii for the names and boundaries used in this map.

Source: MapBiomas. 2023. MapBiomas Use and Coverage 2023. [Accessed on 21 October 2025]. In: MapBiomas. Available at: https://plataforma.brasil.mapbiomas.org/coverage

Mechanisms and extent of temperature increase

When tropical forests are removed, albedo (radiation reflection) increases, and there is a steep reduction in evapotranspiration and the heat that was being dissipated through it. This leads to an increase in sensible heat, which causes an increase in land surface temperature (LST) (Bright *et al.*, 2017).

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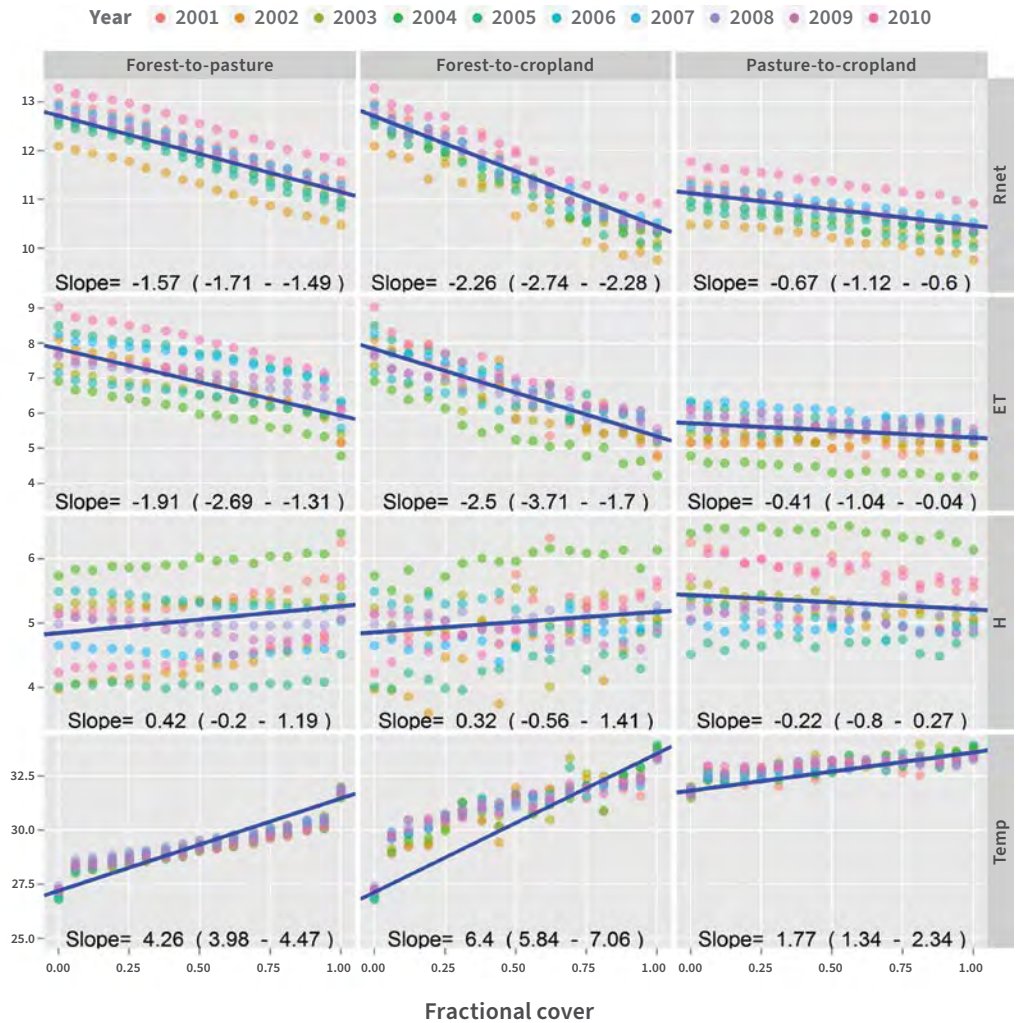
In the southeastern Amazon, in the Xingu basin, there were large changes to land cover in the period 2000–2010, with forest cover decreasing by 12 percent and the majority giving place to pastureland. This led to changes in both energy budgets and the water cycle, which had consequences for LST in the region. The conversion of forest to pastureland led to a decrease in evapotranspiration by 24 percent and an increase in sensible heat by 9 percent. Consequently, LST in deforested areas increased by almost 5 °C (Silvério *et al.*, 2015). Similar rates were also found for the whole Cerrado biome, with evapotranspiration decreasing by 39 percent and LST increasing by an average of 3.5 °C (Rodrigues *et al.*, 2022).

Figure D. *Changes in net radiation, latent heat, sensible heat and land surface temperature as a function of land cover*



Notes: Changes in net radiation (R_{net}), latent heat (ET), sensible heat (H) and land surface temperature (Temp) as a function of fractional change in land cover, estimated from annual remotely sensed data (dots) using linear regressions (solid lines). The slopes in parentheses indicate the minimum and maximum slopes calculated for each year during the period 2001–2010. Temperature is in degrees Celsius, and other variables are in megajoules per square metre per day.

Source: Silvério, D.V., Brando, P.M., Macedo, M.N., Beck, P.S.A., Bustamante, M. & Coe, M.T. 2015. Agricultural expansion dominates climate changes in southeastern Amazonia: the overlooked non-GHG forcing. *Environmental Research Letters*, 10(10): 104015. https://doi.org/10.1088/1748-9326/10/10/104015

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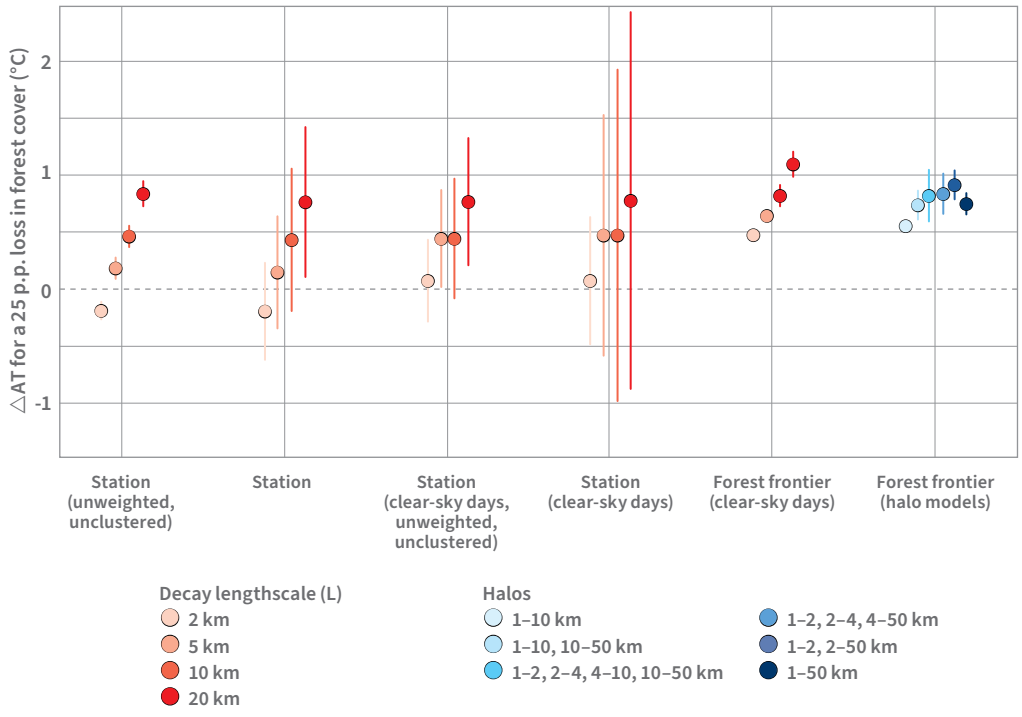
This relation between deforestation and LST also has observable consequences for regional surface and air temperatures. Large changes to land use, as the ones observable in the Amazon-Cerrado region, can lead to changes in surface temperature observable up to 100 km away, with a loss of 100 m^2 causing a fourfold increase in surface temperature, and the removal of an area of 500 m^2 of forest inducing a 14-fold increase (Butt *et al.*, 2023). Regional changes to air temperature are not straightforward, as air currents dissipate and transport the heat released by pasture- and croplands. Nevertheless, for the Amazon-Cerrado region, local deforestation has been shown to influence air temperatures up to 50 km away from the temperature observation point, and to increase maximum temperatures by over 0.5 °C when a quarter of the region within this 50 km radius is deforested, and by over 2 °C when all the forest within the 50 km radius is removed (Alkama and Cescatti, 2016; Cohn *et al.*, 2019). The microclimatic changes induced by deforestation have direct effects on regional agricultural systems, intensifying heat stress for crops and reducing soil moisture content and water availability, while simultaneously increasing climatic variability and the associated risk of yield reductions.

Figure E. *Predicted increase in daily maximum air temperature caused by a 25-percentage point decrease in forest cover within 50 km of the location of temperature observation*



Notes: The figure contains two panels. The left panel shows the response of daily maximum air temperature (ΔAT) based on coefficients estimated using models representing non-local forest cover loss with the non-local forest cover loss metric NLL, where NLL was computed for a range of decay length scales (indicated by marker colours). In this panel, we show predictions for three datasets: the "stations" dataset, the subset of station records consisting of clear skies at the time of one or both of the daytime MODIS overpasses, and the forest frontier dataset (which consists of clear-sky days only). In the case of the "stations" dataset, we include both predictions from a specification without weighting and clustered standard errors (far left) and predictions with weighting and clustered standard errors (second from left). The former can be understood as the average response of maximum temperature to NLL at the locations of weather stations and the latter the sampling region average response. In the rightmost panel, we show predictions derived from the halo specification of forest cover loss. Here, we show results for the "forest frontier" dataset only. Colours indicate alternative aggregations of halos in the specification of the underlying regression models. We estimated all models in the halo panel with weights and clustered standard errors.

Source: Cohn, A.S., Bhattarai, N., Campolo, J., Crompton, O., Dralle, D., Duncan, J. & Thompson, S. 2019. Forest loss in Brazil increases maximum temperatures within 50 km. *Environmental Research Letters*, 14(8): 084047. https://doi.org/10.1088/1748-9326/ab31fb

Sources: See full box references at the end of the bibliography section.

BOX 7

An evolving evidence base

The evidence base for the way forests, trees, deforestation and climate interact comprises a large and diverse literature with differing scales, methods and disciplinary perspectives. Because the interactions manifest at all scales, from the planetary to the farm, understanding their dynamics requires distinct methodological toolkits, research approaches and types of evidence.

Earth system models and their downscaled variants are the main tool used at the global and continental scales to obtain insights into the effects of forests and forest loss on atmospheric circulation, carbon balance and planetary energy fluxes (Boysen *et al.*, 2020; de Hertog *et al.*, 2022; Winckler, Reick and Pongratz, 2017).

Moisture-tracking models provide a complementary set of approaches. These explicitly quantify the origin, fate and recycling of atmospheric moisture, thus allowing researchers to map the pathways by which forest evapotranspiration contributes to precipitation downwind. Such models have been central to estimating how deforestation alters rainfall distribution, both regionally and across continents (Spracklen, Arnold and Taylor, 2012; Tuinenburg, Theeuwen and Staal, 2020).

At the regional and subnational scales, advances in remote sensing and regional climate modelling have enabled detailed assessments of forest cover change, evapotranspiration, surface temperature anomalies and rainfall patterns (Alkama and Cescatti, 2016; Duveiller, Hooker and Cescatti, 2018; Vargas Zeppetello *et al.*, 2020). These studies tend to focus on areas where the forest–agriculture frontier is expanding rapidly, capturing both local warming and broader atmospheric circulation responses.

At the farm to landscape scale, direct measurements such as micrometeorological towers, soil sensors, flux towers and other ground-based networks provide empirical evidence of forest–climate linkages as they affect agriculture and livelihoods. Landmark efforts include the Anglo–Brazilian Amazonian research: the Climate Observational Study (ABRACOS) campaign, the Large-Scale Biosphere–Atmosphere Experiment in Amazonia (LBA), and IPAM/Woodwell Climate Research Center's Tanguro field station, which established multisite observations of surface energy, water and carbon fluxes and helped clarify forest–pasture climate contrasts (Avissar *et al.*, 2002; Gash and Nobre, 1997).

The closer the observational scale is to the landscape, the greater the capacity to empirically measure and attribute forest–climate interactions. Research on forest–climate interactions spans a wide array of fields, including Earth system science, hydrology, meteorology, agricultural science and social science. Together, these contributions have advanced cross-disciplinary understanding of how forests mediate agricultural outcomes through carbon storage and their influence on microclimates, water cycles and resilience to extreme events. The diversity of methods and scales is a significant challenge for integrating forest–climate evidence into a coherent synthesis and thereby into actionable insights for policy- and decision makers.

Brazil is a pioneer in forest–climate research, and it also accounts for a large part of the evidence base on this topic. Several factors explain the country's prominence: high historical and current rates of deforestation; forest frontiers with major concentrations of crop and livestock production; and a strong domestic scientific community in atmospheric sciences, ecology and agricultural economics. The Brazilian evidence base includes assessments of temperature-related changes (Alves De Oliveira

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et al., 2021; Baker and Spracklen, 2019), changes in large-scale climate patterns (Bochow and Boers, 2023; Commar, Abrahão and Costa, 2023), changes in the intensity and length of the dry season (Costa and Pires, 2010), changes in the distribution and intensity of precipitation (Leite-Filho, de Sousa Pontes and Costa, 2019), changes in the effects of climate change (Franco *et al.*, 2025; Qin *et al.*, 2025), and implications for farmers and the economy (Rattis *et al.*, 2021; Rebelatto *et al.*, 2022).

The Amazon basin is the best-studied region, but there is also a growing body of literature focused on other tropical regions, expanding both the geographical scope and the methodological diversity. In West Africa, convection-permitting regional models have been used to simulate the effects of historical deforestation on monsoon rainfall (Crook *et al.*, 2023; Hartley *et al.*, 2016), complemented by basin-scale reforestation and greenbelt studies using downscaling approaches (Oguntunde *et al.*, 2014; Saley *et al.*, 2019). In the Sahel, modelling of large-scale afforestation projects such as the Great Green Wall has investigated implications for rainfall extremes and temperature variability (Saley *et al.*, 2019). Analyses of tropical forest loss in Indonesia and on the island of Borneo employ regional models and satellite data to detect impacts on daily temperature variability and hydrological extremes (Ge *et al.*, 2022; Li *et al.*, 2022). Comparative global-scale analyses indicate consistent patterns of rainfall reduction and warming associated with tropical deforestation (Smith, Baker and Spracklen, 2023).

Evidence produced at a growing range of locations using diverse methods and posing differing research questions is underscoring the centrality of forests in shaping agricultural futures under climate change. It suggests that deforestation not only contributes to global climate change through greenhouse-gas emissions but also undermines regional hydrological stability, increases temperature extremes, and generates cascading risks for food production. Although questions remain about the magnitude and extent of these effects, especially at larger spatial scales, the convergence of findings across disciplines and methodologies adds credibility to the conclusion that conserving forests is indispensable for climate resilience and agricultural sustainability.

Sources: See full box references at the end of the bibliography section.

CLIMATE CHANGE IMPACTS ON THE CLIMATE BENEFITS OF FORESTS

The extent to which the climate-regulation benefits of forests for agriculture will continue is highly uncertain, given the accelerating impacts of climate change (IPCC, 2023a). Increasing concentrations of greenhouse gases in the atmosphere are expected to cause temperatures to rise and to change precipitation patterns and global atmospheric and oceanic circulation patterns (IPCC, 2023a). Climate change is projected to be a major driver of degradation in precipitation recycling, which is projected to occur at a rate of about 1.5 percent per 1 °C of global warming. The projected decline in recycling potential is likely to be exacerbated by deforestation, which, in some regions, contributes to reduced evaporation and precipitation, ultimately leading to a decline in precipitation supply. This includes ecologically crucial phenomena, such as global monsoon patterns, storm tracks, and the heat transported by ocean currents.

Scenarios included in the Sixth Assessment report (AR6) of the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2023b) depict futures that range from 1.5 °C warmer to more than 5 °C warmer by 2100. Such changes in global temperature will be associated with a broad range of changes in precipitation and resultant soil moisture, with consequences for forests globally.

The IPCC AR6 summarized the spatial patterns and magnitudes of temperature, precipitation and soil moisture changes under future global warming levels of 1.5 °C, 2 °C and 4 °C relative to pre-industrial global temperature levels (circa 1850–1900). All terrestrial areas are projected to become warmer, with local warming over land increasing at least as fast as the global average. In contrast, the spatial distribution of precipitation is not projected to change uniformly under warming scenarios. Some parts of the world (e.g. South Asia and the high-latitude regions of Eurasia and North America) are projected to experience increases in precipitation, while others (e.g. South America, especially the Amazon, and the Mediterranean) are projected to experience declines. The combination of changes in temperature and precipitation is projected to lead to substantial changes in soil moisture under future warming levels, with much of North and South America experiencing declines, including sharp declines in the Amazon region. In Africa, soils may become wetter in the Sahel and some tropical forests. Soil moisture is projected to decrease in southern Europe and increase in Central Asia. The direction of change in tropical Southeast Asia is unclear.

Climate change will increase the variability of climate-regulation benefits provided by forest

ecosystems. Globally, forests are projected to shift as climate zones move towards the poles and upward along altitude gradients. This may lead many forest ecosystems to shrink or even collapse, with significant consequences for agricultural productivity. In many parts of the world, intact natural forests may be isolated in patches, such as protected areas. Such forests, and the species within them, will be less able to "migrate", given their highly fragmented nature. Data from an analysis of protected areas in Finland (Heikkinen *et al.*, 2020) indicate major shifts in climate in all existing protected areas by the end of the century, which could mean that forests in those areas will almost completely disappear unless ecosystems can be linked in ways that permit species migration. There is evidence that species adapted to narrower ranges of climatic conditions, such as those close to the equator, will find it more difficult to adapt to the pace of climatic change (Carroll *et al.*, 2015). Changes in the range distributions of pests and diseases will also challenge the viability of forests. A growing literature suggests the potential for regime shifts in local and regional ecosystems, particularly in tropical landscapes (Hirota *et al.*, 2011).

Agriculture faces multiple risks arising from changes to forest ecosystems under climate change. For example, climate change may lead to the drying-out of some terrestrial areas relative to oceans (Findell *et al.*, 2019), which would disrupt the various roles that forests play in regulating local, regional and distantly connected climates. At large scales, hotter and drier conditions (both in terms of precipitation and soil moisture) may threaten the role of forests in continental moisture recycling networks (Staal *et al.*, 2025).

Changes to maximum and minimum temperatures will shift habitat distributions, giving rise to the notion that ecosystems will need to migrate to keep pace with ideal habitat conditions (Loarie *et al.*, 2009). The regulating benefits of forests for local and regional climates will shift as well, especially in terms of cooling benefits associated with forest evapotranspiration and moisture recycling (Seymour, Wolosin and Gray, 2022).

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TRADE-OFFS AND SYNERGIES AMONG COMPETING GOALS IN THE FOREST–CLIMATE–AGRICULTURE NEXUS

The interplay between agriculture and forests at large scales can involve complex trade-offs with significant implications for climate stability and food security. Cross-sectoral synergies are needed to enhance agricultural production while maintaining the forest cover needed to sustain climatic and hydrological processes. In some regions, agricultural expansion leads to deforestation in areas where forests play crucial roles in regulating rainfall patterns, moderating temperatures, and stabilizing regional climates. Such deforestation can result in outcomes in which short-term agricultural gains undermine the environmental conditions on which agriculture depends and ultimately reduce productivity and profitability (Leite-Filho, Soares-Filho and de Oliveira, 2024). It is important to consider the direct benefits that forests provide for agriculture by conserving biodiversity, protecting soils and regulating local and regional climate systems.

The climatic and hydrological benefits – such as moisture recycling and rainfall support – provided by forested areas are often felt far beyond the forest boundary (Keys and Wang-Erlandsson, 2018). For example, forests in upwind regions can influence precipitation patterns hundreds of kilometres away. This spatial disconnect means that those who bear the costs of conserving forests are not always the same stakeholders who reap the agricultural benefits. Addressing these trade-offs requires policies and incentive mechanisms that operate across scales and jurisdictions to align interests, distribute costs and benefits fairly, and sustain forest functions crucial for agriculture.

A further layer of complexity arises from differences between forest types and management practices. Natural forests and forest plantations are not ecologically equivalent. Although plantations can contribute to carbon sequestration and economic objectives, they often lack the structural diversity, biodiversity and hydrological functions of natural forests. Large-scale afforestation projects, especially when implemented without careful

ecological planning, can inadvertently create perverse outcomes, such as by altering local water cycles, reducing albedo and displacing natural ecosystems (Xiao, Xiao and Sun, 2020). It is essential, therefore, that both conservation and afforestation initiatives consider not only how many trees are planted or protected but also their locality and species and how the ecosystems will function to support climate and agricultural resilience.

Effectively navigating trade-offs demands integrated land-use strategies that recognize both local agricultural priorities and the broader climate-regulating roles of forests to ensure that actions at one scale do not undermine sustainability at another.

KNOWLEDGE GAPS

Several substantial knowledge gaps can be identified in the understanding of interactions between forests, climate and agriculture. The first relates to the non-linear effects arising from different spatial patterns of deforestation, forest types (e.g. primary, secondary or plantation), species assemblages, and location. Scientific and cultural knowledge on these effects is scattered across scholarly and grey literature, and much is held in disciplinary "silos". There is an urgent need to bring these strands of knowledge together and improve understanding of how these diverse conditions affect the benefits that forests and trees can provide. This is particularly important when it comes to understanding optimal mosaic landscapes for the provision of ecosystem services, the potential effects of large-scale afforestation, and the capacity of restoration to provide similar benefits to primary forests.

Secondly, there is a need to better understand the dynamic geophysical and ecological consequences of deforestation in agricultural regions, especially in terms of precipitation patterns. While forest, water and land-use monitoring has advanced significantly and remains an important tool, it is essential to better link these efforts and understand forest–climate–agriculture interactions through interdisciplinary approaches and local-scale measurements. Nearly all scenarios of land-use and land-cover change used for projecting climate change depict radically different distributions of forests globally by 2100. There is a misalignment between these land-cover scenarios, and the quantification of the consequences that such changes might have for global atmospheric circulation patterns and the distribution of precipitation regionally.

Finally, the socioeconomic and cultural connections between agricultural areas, both adjacent to and distant from deforestation, and upwind forested areas could be better understood to inform policies that increase forest resilience on a regional scale. Substantial social science research is needed to understand these links (Seymour, Wolosin and Gray, 2022).

CONCLUSIONS

Across all scales, evidence shows that forests are not only carbon sinks but active regulators of the climatic conditions that sustain agriculture. Through evapotranspiration, canopy roughness, albedo and biogenic emissions, forests influence temperature, precipitation and moisture flows, shaping both local microclimates and continental rainfall patterns. Forests are crucial for modulating the climate of nearby and distant agriculture. Intact healthy forests contribute to stable climate regimes, especially in dry periods, by ameliorating temperature extremes.

Climate change threatens to unravel much of the knowledge and relationships with the land that agricultural communities have accumulated and formed over centuries. Temperature changes, especially with regard to temperature extremes, in deforested landscapes increase the likelihood of soil moisture deficits and drought, and the associated greater prevalence of fire and increased vulnerability to pests and diseases. Changes in rainfall quantity (i.e. how much?) and seasonality (i.e. when will it fall?) will not only affect forests but also the agricultural communities that rely on these dynamic but inherently stable climate regimes.

The effects of forests and trees on agriculture happen at different scales at the same time; at regional and continental scales, forests sustain precipitation and buffer climatic extremes, while local forests moderate heat and drought, stabilize rainfall and improve soil moisture. These interconnected processes link distant landscapes: moisture generated by forest evapotranspiration travels across borders and sustains rainfed production far from its source. Agricultural areas worldwide rely on forests in other countries for annual precipitation, underscoring the transboundary nature of forest–climate–agriculture interactions.

These cross-scale linkages mean that local adaptation measures have the potential, but cannot on their own, offset the effects of large-scale forest loss. Coordinated management across jurisdictions and scales is essential to preserve the climatic benefits that underpin food production. However, the forest–agriculture relationship has been defined by trade-offs. Short-term gains from deforestation often undermine long-term climate stability, while poorly designed afforestation can disrupt hydrological cycles or replace natural ecosystems. Effective policies must therefore consider where and how forests are conserved or restored, prioritizing ecological function and agricultural resilience over simplistic targets of tree cover.

Under a changing climate, the ability of forests to regulate temperature and precipitation will become increasingly variable and uncertain. Sustaining these benefits will require integrated monitoring, coupled biophysical and social modelling, and governance frameworks that align agricultural development with forest conservation.

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CHAPTER 4

The critical role of forests and trees in regulating the water cycle

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KEY MESSAGES

- **Forests and trees – on or near agricultural land but also hundreds of kilometres away – can provide a range of water-related ecosystem services critical for agriculture, including freshwater supply, regulation of water flows, local climates and temperatures, as well as water damage mitigation, and water purification.**
- **The water-related ecosystem services from trees and forests to agriculture are insufficiently monitored and valued, which means that they are under recognized in the agricultural sector and agriculture-related policies, resulting in economic losses for farmers and countries.**
- **An integrated approach to landscape and natural resource management – forests and water – at various scales is essential for ensuring that the benefits of forests and trees for agriculture are optimized. Decision-support systems that consider trade-offs and synergies among the forest ecosystem services provided are emerging as key tools to facilitate this.**

INTRODUCTION

Freshwater quantity, quality and timing is critical for agricultural production. Forests and trees are essential for delivering many water-related ecosystem services, including water provisioning and supporting an intact and reliable hydrological cycle. Interactions between trees, forests and water (i.e. the forest–water nexus) underpin the delivery of essential ecosystem services for people and the planet. This chapter focuses on the critical role of forests and trees in regulating the water cycle and on the essential benefits that this regulation delivers for agriculture.

FRESHWATER RESOURCES IN AGRICULTURE

Rainfed agriculture, including rainfed crop and pasture systems, represents 80 percent of the total arable land globally and supports about

two-thirds of the world's crop production (Oki and Kanae, 2006; Wilderer, 2011). Most farmers worldwide are thus heavily dependent on reliable precipitation patterns to recharge the soil water (green water) that will sustain their crops and forages. The remaining third of the global crop production relies on withdrawn surface water and groundwater (blue water) for irrigation. Notably,

BOX 8

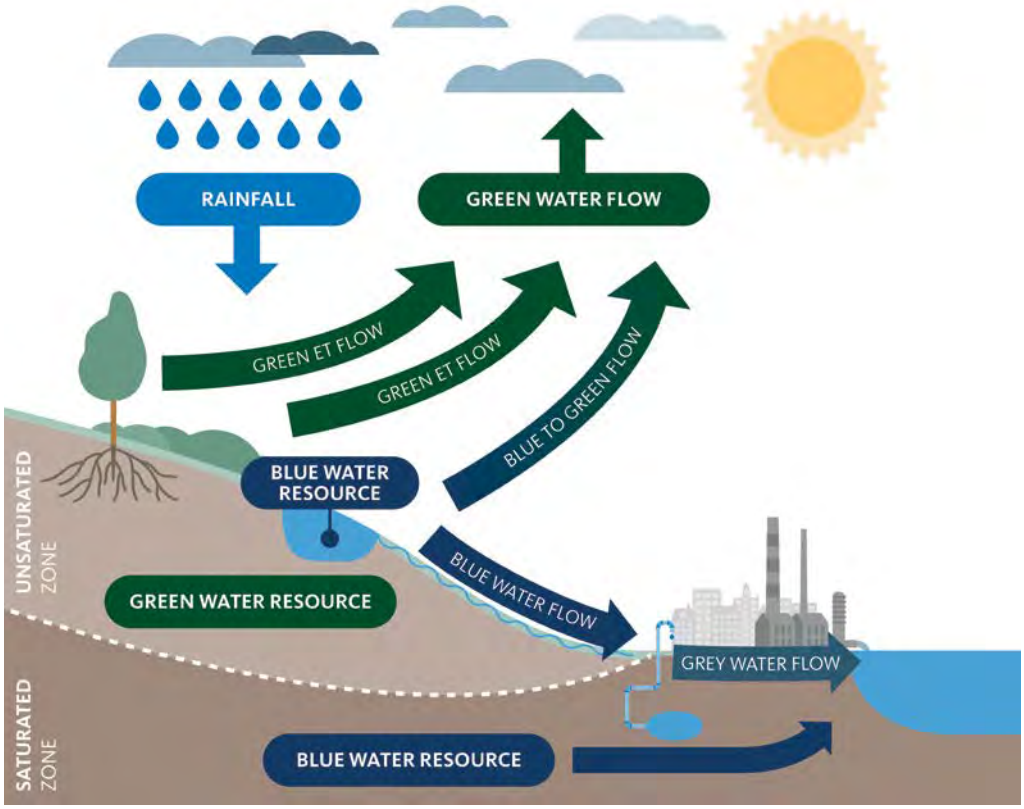
Freshwater resources

The Earth's freshwater resources can be broadly divided into:

- ***green water:*** soil moisture available to plants, and evaporation and transpiration flows from soil and vegetation;
- ***blue water:*** water in lakes, rivers, wetlands, groundwater, glaciers and impoundments such as dams; and
- ***grey water:*** potentially polluted water from domestic and industrial activities.

The green, blue and grey water categories provide a way of understanding how different freshwater resources are used and accessed within the hydrological cycle (**Figure F**).

Figure F. *The water cycle and its green, blue and grey freshwater stores and flows*



Note: Blue water: surface and groundwater (e.g. rivers and lakes, groundwater and the water frozen in glaciers and the polar ice caps); green water: soil moisture from rainfall available to plants and trees (green water stores); plant transpiration and soil evaporation (green water flows); grey water: polluted water from domestic and industrial activities.

Source: SIWI. 2025. *Water-Smart Forest and Landscape Restoration Tool: Water-smart forest and landscape restoration.* By Ingermarsson L.M., Mingasson, D. & Tengberg, W. https://siwi.org/wp-content/uploads/2023/11/w-flr-tool-handbook_beta-version_feb-24.pdf

Source: SIWI (2025). See **Figure F** at the end of the bibliography for full box reference.

these irrigated areas account for 20 percent of the total arable land globally and about 70 percent of global freshwater use (McDermid *et al.*, 2023). In many countries with developing economies, water resources are scarce, and food production is largely rainfed. Due to the effects of climate change, the demand for freshwater resources is projected to increase in all major sectors, such as for domestic use, industry, energy production and agriculture (Ingemarsson *et al.*, 2022). To ensure water and food security, it is therefore of utmost importance to develop and adopt agricultural systems that are efficient and productive from a water perspective, both under rainfed and irrigated conditions.

Land-use changes over the past 50 years have had major negative impacts on local hydrological processes, with agricultural expansion contributing to deforestation, altered rainfall patterns and reduced agricultural yields (Mazzucato *et al.*, 2024). Given the increasing demand for freshwater, it is urgent to adopt measures that enhance water productivity –the amount of agricultural output produced per unit of water used. By adopting land management practices that enhance the productive use of water in agriculture, farmers could increase agricultural productivity without putting additional strain on water resources. Practices that promote water productivity involve reducing evaporative water losses (e.g. through mulching), enhancing plant water uptake capacity (e.g. by using drip irrigation systems), and reducing surface runoff losses by collecting runoff and improving water infiltration into the soil (e.g. water harvesting techniques) (Descheemaeker *et al.*, 2013). In many countries with developing economies, water resources are scarce, and food production is largely rainfed.

THE TREE AND FOREST–WATER NEXUS

Trees take up water through their roots to support photosynthesis. Most of this water is released to the atmosphere via transpiration. Some rainfall is also intercepted by leaves and other plant surfaces and evaporates directly (i.e. interception). Through those processes, forests and trees are integral to the global water cycle and, thus, to many provisioning, regulating, supporting and cultural ecosystem services that rely on it. On a local scale, forests and trees regulate streamflow, fostering groundwater recharge and dry season flow in streams, and reducing surface runoff, peak flows and the risk of flooding. They also act as natural filters, reducing soil erosion and water sedimentation, thus providing high-quality water for human consumption, agriculture and the environment.

Despite significant advances, some of the mechanisms by which trees and forests influence water resources and flows remain incompletely understood, and certain misconceptions, such as that more trees always mean less water, are still widespread (Sheil and Bargués Tobella, 2020). All trees use water, but in recent years, research has shown that tree water use should not only be viewed as a loss. Instead, it is now recognized that water evapotranspired by trees contributes to rainfall generation in downwind locations (Ellison *et al.*, 2017). These processes are site-specific and influenced by local conditions, such as climate, topography, elevation, and vegetation cover. The likelihood of rain depends on atmospheric moisture, meaning that the presence of more trees can increase the rainfall frequency of the same water on land, on the same piece of land or far away, before it departs back to the ocean (Keys, Wang-Erlandsson and Gordon, 2016). This was explained in detail in **Chapter 3**.

EXTREME HYDROCLIMATIC EVENTS AND AGRICULTURAL DROUGHTS

Many of the world's farmers have already been forced to adapt to changing precipitation patterns and more frequent extreme weather and climate events, such as heavy rainfall and drought. Climate change is expected to increase the frequency and severity of these extreme hydroclimatic events (Ingemarsson *et al.*, 2022). Water availability is largely determined by precipitation and evapotranspiration. Agriculture can experience drought either from rainfall deficit (meteorological drought), lack of sufficient soil moisture (agricultural and ecological drought, depending on the system in focus), or lack of surface or groundwater for irrigation (hydrological drought). Agricultural and ecological drought is induced by increased atmospheric evaporative demand as well as reduced replenishment of soil moisture due to the degradation of soil structure. Thus, while more heavy rainfall has the potential to enhance the replenishment of soil moisture, degraded soils with low infiltration capacity can experience increased surface runoff, exacerbating soil erosion (Bargués Tobella *et al.*, 2020). With reductions in soil moisture, the land carbon sink will become less efficient, driving a feedback loop, which may lead to even higher greenhouse-gas emissions. Forests and trees can help mitigate the impacts of agricultural drought and extreme hydroclimatic events as a result of forest–water interactions that will be explained in subsequent sections.

MECHANISMS BY WHICH TREES AND FORESTS CAN INFLUENCE WATER RESOURCES AND THE HYDROLOGICAL CYCLE

Trees and forests affect the water cycle, including its green and blue water resources and flows, through multiple mechanisms (**Table 7**). These mechanisms influence different hydrological attributes – the quantity, quality and timing of water flows, in other words, the regulation of the hydrological cycle – and, in turn, the provision of water-related ecosystem services (Creed and Van Noordwijk, 2018), leading to positive and negative implications for agriculture and food production, and possibly both.

Trees and forests affect key hydrological processes such as evaporation, transpiration, precipitation, infiltration and groundwater recharge, thereby influencing the flow and distribution of water within landscapes and between the atmosphere and terrestrial environments at different scales (local, regional and even global). Farmers, pastoralists, foresters, and other land users and managers need to be aware of the links between forests, trees and water, and hold knowledge in how to optimize hydrological attributes and support water-related ecosystem services.

Table 7. *Mechanisms by which trees and forests influence water resources and the hydrological cycle, their effects, and the resulting main hydrological attributes and key impacts on agriculture*

SCALE: LEAF AND TREE			
MECHANISM	**EFFECT**	**HYDROLOGICAL ATTRIBUTE**	**IMPACT ON AGRICULTURE**
Stem water storage	Trees store water, allowing them to maintain high transpiration even in periods when uptake from the soil is limited; this allows trees to emit vapour over more extended periods, thus influencing atmospheric moisture.	Water flow regulation	Impacting local-scale atmospheric moisture (green water flows)
SCALE: TREE AND STAND			
MECHANISM	**EFFECT**	**HYDROLOGICAL ATTRIBUTE**	**IMPACT ON AGRICULTURE**
Infiltration	The entry of water into soil, controlling surface runoff generation and soil and groundwater recharge.	Water quantity, quality and flow regulation	Improving the recharge of soil moisture (green water stores), groundwater (blue water stores), and the regulation and quality of blue water flows
Preferential flow	The flow of infiltrating water along preferred pathways in the soil, including macropores formed by roots and soil fauna.	Water quantity	Improving the recharge of groundwater (blue water stores)
Transpiration	The process by which trees extract water from the soil or groundwater and emit it to the atmosphere as vapour.	Water quantity	Reducing blue water flows and soil moisture (green water stores), and enhancing local-scale atmospheric moisture (green water flows)
Interception	Prevents some rain from reaching the soil surface (evaporates back), also reducing the speed of falling rainwater on the surface of the forest floor, thus potentially reducing surface runoff and erosion.	Water quantity and quality	Reducing blue water flows and soil moisture (green water stores) and enhancing local-scale atmospheric moisture (green water flows)
Fog and cloud interception by trees	Interception of fog and clouds provides significant amounts of moisture in certain locations and seasons.	Water quantity	Enhancing blue water flows and the recharge of soil water (green water stores)

Soil evaporation	Improved microclimate under tree canopies reduces unproductive water losses through soil evaporation.	Water quantity	Improving soil moisture (green water stores)
Litter mulch	Affects how much water enters the soil; reduces soil temperature, soil evaporation and surface runoff.	Water quantity and flow regulation	Enhancing soil moisture (green water stores) and improving the quality of blue water
Reducing erosion	Tree roots and soil organic matter from litter inputs bind soil particles and slow down water movement.	Water quality	Reducing soil movement, sedimentation in streams, and the risk of disturbances, such as flows of debris and slope failures
Filtering and absorbing nutrients	Trees can absorb excess nutrients such as from agricultural runoff.	Water quality	Improving water quality (blue water stores and flows)
Filtering and degrading pollutants	Forest floor leaf litter, roots and soil microorganisms trap and decompose pollutants.	Water quality	Improving water quality (blue water stores and flows)
Albedo	Forest canopies absorb incoming solar radiation.	Water quantity	Enhancing local-scale atmospheric moisture (green water flows)
Atmospheric mixing	Forest and trees return energy and moisture to the atmosphere, thereby cooling the land surface and promoting precipitation.	Water quantity	Impacting local-scale atmospheric moisture (green water flows)
Deep water uptake	Some trees obtain water from much deeper in the soil profile (including groundwater) than other vegetation and can thus emit vapour over more extended periods, which influences atmospheric moisture.	Water quantity and flow regulation	Impacting and regulating blue water flows; impacting local-scale atmospheric moisture (green water flows)
Hydraulic redistribution	Deep-rooted trees, especially those with dimorphic root systems, passively redistribute water from moist to dry soil layers via their roots.	Water quantity and flow regulation	Impacting soil moisture (green water stores); impacting and regulating blue water flows; impacting local-scale atmospheric moisture (green water flows)
SCALE: STAND TO CATCHMENT/REGION*			
MECHANISM	**EFFECT**	**HYDROLOGICAL ATTRIBUTE**	**IMPACT ON AGRICULTURE**
Soil water-holding capacity	Trees often contribute to, and maintain, soils with comparatively good water storage capacity.	Water quantity	Impacting soil moisture (green water stores)

Note: * Additional catchment- or region-scale mechanisms related to evapotranspiration and temperature, among others, are covered in Chapter 3 of this report.

Source: Adapted from Sheil, D. & Bargués Tobella, A. 2020. More trees for more water in drylands: myths and opportunities. *ETFRN News*, 60. https://hdl.handle.net/10568/111705

The effects of forests and trees on water quantity are important for agriculture because water quantity – in terms of green (soil moisture) and blue (surface and groundwater) water resources – is critical for agricultural production. Trees and forests can improve soil moisture, groundwater recharge and streamflow by improving soil infiltration capacity, that is, the ability of soils to absorb water at the soil surface (Bargués-Tobella *et al.*, 2024; Mens *et al.*, 2023; Zwartendijk *et al.*, 2025). Trees and forests can also improve soil water retention and water-holding capacities (Bayala *et al.*, 2006; Calder, 2007). Thereby, forests and trees may directly affect water supply for agricultural production. In general, reforestation may reduce total annual streamflow due to higher

evapotranspiration losses from increased tree cover, while deforestation can increase it at least in the short-term perspective (Jackson *et al.*, 2005). Exceptions may include montane cloud forests where fog interception increases water inputs (Bruijnzeel, Mulligan and Scatena, 2011). In degraded soils, forests and trees can enhance groundwater recharge and dry season flows in streams if the soil infiltrability is improved and the gains from increased infiltration overweigh the losses from increased evapotranspiration (Bruijnzeel, 2004; Ilstedt *et al.*, 2016; Krishnaswamy *et al.*, 2012, 2013). The magnitude of these evapotranspiration losses depends on species traits (e.g. canopy and root architecture, phenology) and can be reduced through management practices like tree pruning, spatial arrangements and mulching. While these "losses" reduce soil and groundwater locally, the water vapour returned to the atmosphere can contribute to rainfall in downwind locations – both far away but even locally (i.e. local rainfall recycling) (see **Chapters 3** and **4** and the references therein). Through the effective management of forests and trees, farmers and other land managers can improve soil moisture, groundwater recharge and dry season flow in streams and thus avoid unnecessary periods of water stress.

The effects of forests and trees on water quality are important for agriculture because they play a crucial role in maintaining and improving the quality of the water that flows into human settlements and irrigation systems. Forested landscapes serve as a natural infrastructure for water purification (Qiu *et al.*, 2023). Forest ecosystems can act as buffers against water pollution by absorbing nutrients, trapping sediments and reducing the transport of chemical pollutants. Tree roots stabilize soil, reducing erosion and subsequent siltation of waterbodies (Bruijnzeel, 2004; Zhu *et al.*, 2018). Land management that exposes soil often has strong implications for water quality, where operations such as crop and timber harvesting, and soil preparation and fertilizing can reduce water quality by increasing the amounts of sediment, nutrients and chemicals in waterbodies. Water quality varies in space and time, and forests usually can mitigate these fluctuations. Open water in upstream forests generally has lower levels of particles, compared to downstream forests, which are often more exposed to neighbouring land management operations. Incorporating forests and trees into agricultural landscapes and maintaining and promoting riparian forests and forest buffers can significantly prevent contamination of water systems and enhance the quality of water for irrigation, livestock, and household use.

The effects of forests and trees on water timing and flow regulation are important for agriculture because the regulation of water flows – when and how water is available – is critical for crop and livestock production, particularly in regions with limited infrastructure to store or manage water. Trees and forests influence how water is absorbed, stored and released into the environment, affecting both the short-term and long-term hydrological cycles that directly impact agricultural production. It is often explained that forests and trees influence water flows by acting as natural sponges and regulators. During periods of excess rainfall, forests can absorb and retain water, reducing the risk of floods (Ellison, 2018; Zhang *et al.*, 2017). This "storage" is primarily the result of the high hydrological functioning that characterizes most forest soils, which ensures that water at the soil surface enters the soil and slowly recharges groundwater stores. During dry periods, groundwater stores sustain dry season flow in streams (Bruijnzeel, 2004). Farmers and pastoralists around the world are heavily reliant on secure and perennial water supplies. In areas with limited water infrastructure, rural communities prefer a reliable access to streamflows rather than increased total annual streamflow, which highlights the importance of flow regulation above quantity (Sandström, 1998). While forests usually reduce total annual streamflow, they tend to improve dry season flow in streams compared to non-forested lands with degraded soils (Bruijnzeel, 2004; Ilstedt

et al., 2016; Krishnaswamy *et al.*, 2012, 2013), benefiting rural communities that depend on these flows for agricultural production. As addressed in **Chapter 1**, forests and trees also influence the timing of water flows on a regional to continental scale. For instance, trees release water vapour into the atmosphere through transpiration, which influences local humidity and precipitation patterns but also regional rainfall recycling in tropical areas (Ellison *et al.*, 2017).

In summary, trees and forests play a critical role in shaping the quantity, quality and timing of water resources. The protection and restoration of forest ecosystems as well as the protection and promotion of tree cover in agricultural lands can support a balanced and resilient water cycle. Sustainable forest management is vital to promote benefits and mitigate potential trade-offs, ensuring water security for human and ecological needs.

Based on the mechanisms by which trees and forests influence the water cycle, we now focus on four types of potential benefits from forests and trees to agriculture at the local scale:

- Improving soil moisture (green water stores).
- Improving and regulating blue water flows.
- Improving local-scale atmospheric moisture (green water flows).
- Improving the quality of water used for irrigation (blue water stores and flows, such as reservoirs and rivers).

Improving soil moisture (green water stores)

In rainfed crop and pasture systems, soil moisture originating from infiltration following precipitation sustains crops and forages. In these systems, integrated soil and water management practices are fundamental to enhancing crop and livestock productivity and the provision of other vital ecosystem services such as erosion control (Barron and Tengberg, 2023; Falkenmark, Rockström and Karlberg, 2009; Rockström, Barron and Fox, 2003). Agroforestry, a set of land-use systems in which trees are deliberately grown and managed on the same piece of land used for agricultural crops or livestock, or both (Lundgren and Raintree, 1983), offers opportunities for increased agricultural productivity through enhanced soil moisture (Kuyah *et al.*, 2019).

Trees on farms can have contrasting impacts on soil moisture content. Trees can enhance soil moisture through improved infiltration capacity and retention of soil moisture (Clermont-Dauphin *et al.*, 2023; Kuyah *et al.*, 2019; Siriri *et al.*, 2013). Increased litter inputs and activity of tree roots and tree-associated soil fauna all contribute to building soil organic matter, aggregation and macroporosity (Chirwa *et al.*, 2004), improving soil infiltration and water-holding capacities (Bargués-Tobella *et al.*, 2024; Kuyah *et al.*, 2019; Nyamadzawo *et al.*, 2008). Shading from trees can improve the microclimate under tree canopies and reduce unproductive water losses through soil evaporation, contributing to enhanced soil water content (Benegas *et al.*, 2021; Jackson and Wallace, 1999). In addition, trees on farms can increase the topsoil water content available to crops and forages through hydraulic lift, the process by which trees passively redistribute water from deep, moist soil layers to shallow, dry soil layers via their roots. Several authors have reported this phenomenon in most plants with deep roots, and even in shrubs (Bayala and Prieto, 2020; Ong *et al.*, 2014). Through the process of hydraulic redistribution, woody deep-rooted plants can potentially act as "bioirrigators" to adjacent plants (Bogie *et al.*, 2018; Kizito *et al.*, 2012), buffering against droughts and ensuring productivity in regions with erratic rainfall (Bayala and Prieto, 2020; Lee *et al.*, 2018; Prieto *et al.*, 2011). Trees can reduce soil moisture through increased transpiration and interception losses (Siriri *et al.*, 2013). The magnitude of these losses, as well as water redistribution into throughfall and stemflow, or the effect of trees on soil hydrological functioning, are highly dependent on tree functional traits, including rooting and canopy architecture, leaf traits and deciduousness (Antoneli *et al*., 2021; Bayala *et al*., 2014). Tree leafing phenology is an important factor affecting the temporal complementarity or competition for water between trees and crops; for example, trees with a reversed phenology, such as *Faidherbia albida* (Delile) A. Chev., which is leafless during the wet (cropping) season, are extremely attractive in agroforestry as the competition for water with associated crops is minimal. Trees and crops or forages can exhibit spatial complementarity too,

with some trees exploiting deeper water sources, at least during the dry season when water availability in the upper soil layers is low (Bargués Tobella *et al.*, 2017; Benegas *et al.*, 2021).

Improving soil water available to crops requires careful consideration of the positive and negative impacts of trees and the factors that regulate them. Management is critical to influencing those factors, limiting tree and crop competition for water and maximizing productivity. Besides tree species selection and tree spatial and temporal arrangements, key management practices can boost soil water content, including green manure addition, mulching using tree leaves, and tree shoot or root pruning (Bayala, 2002; Ong *et al.*, 2007; Siriri *et al.*, 2013).

Improving and regulating blue water flows

Trees and forests enhance soil infiltration capacity (Bargués-Tobella *et al.*, 2024; Ilstedt *et al.*, 2016; Nyberg *et al.*, 2012), thereby influencing rainfall partitioning into infiltration and infiltration-excess overland flow (i.e. surface runoff). This partitioning determines the pathways and time needed for water to reach the stream channel and is thus closely linked to streamflow regimes. More infiltration results in enhanced recharge of soil water and, eventually, groundwater, as well as reduced overland flow, leading to a more delayed response in streamflow following a rainfall event. Conversely, reduced infiltration leads to enhanced occurrence of overland flow and a faster hydrological response, with a higher prevalence of "quickflow" and peak flows, and soil erosion. Thus, protecting and promoting tree cover and forests may contribute to reducing the risk of flooding and erosion and to a more sustained streamflow over time.

The impact of tree cover and forests on water yields – both annual streamflow and baseflow or dry season flow – is complex and highly context-specific (Ellison *et al.*, 2017). Because trees consume more water than shorter vegetation types such as grasses or agricultural crops, deforestation typically leads to greater streamflows in the short term and potentially problematic shifts in streamflow timing, while forestation (re- and afforestation) reduces streamflow (Brown *et al.*, 2005; Costa, Botta and Cardille, 2003; Farley, Jobbágy and Jackson, 2005).

However, there are exceptions to this general trend, where tree-cover loss can lead to reduced water yields, and greater tree cover can result in enhanced yields. One such exception is the case of many montane cloud forests where fog and cloud interception by trees provides substantial additional water inputs. Modelled contributions of cloud-water interception range from less than 5 percent of total precipitation in wet areas to more than 75 percent in low-rainfall areas (Bruijnzeel, Mulligan and Scatena, 2011). Thus, when the contribution of occult precipitation to total precipitation is high, conversion of montane cloud forests may lead to reductions in water yields in streams despite reduced transpiration losses from trees, although the opposite might be the case as well (Bruijnzeel, Mulligan and Scatena, 2011).

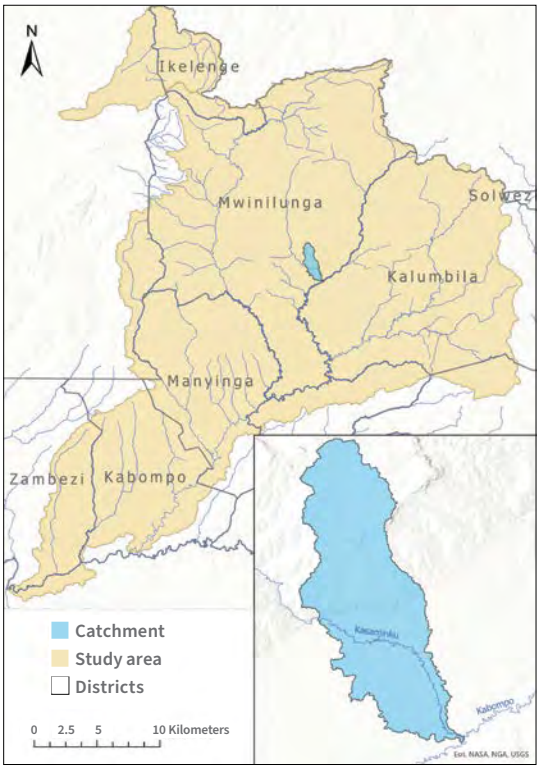
The other case where greater tree cover may enhance water yields, refers to areas with degraded soils and impaired infiltration. Soil structure deterioration, related to deforestation and unsustainable land-use management, can reduce infiltration opportunities and jeopardize the recharge of groundwater stores that sustain baseflow in streams. Increasing tree cover in these soils can contribute to improved soil structure and the restoration of soil hydrological functioning. If the gains from increased tree cover on soil hydrological functioning increase the losses through enhanced evapotranspiration from these trees, greater tree cover can improve groundwater recharge and dry season flows (see **Box 9**; Bruijnzeel, 2004; Ilstedt *et al.*, 2016; Krishnaswamy *et al.*, 2012, 2013). The net effect of changes in tree cover on groundwater recharge and dry season flows will depend on several factors, including local conditions related to climate and soils, the degree of tree cover, tree species and functional traits, and management, among others (see **Box 9**; Ilstedt *et al.*, 2016).

BOX 9

The forest–water–climate nexus in the headwaters of the Zambezi River in Zambia

The Zambezi River basin is one of Africa's largest and most important, extending over Angola, Botswana, Malawi, Mozambique, Namibia, the United Republic of Tanzania, Zambia and Zimbabwe. The headwaters of the river originate in the Northwestern Province of Zambia, which is one of the highest forested areas in the country. The headwater forests regulate water quality, quantity and timing, store large amounts of carbon and regulate local climates. They also provide food, forage, fodder and energy, making them a lifeline for the ecosystems and people in the Northwestern Province and beyond. However, the area faces threats of deforestation and land degradation while being vulnerable to climate change. Understanding forest, water and climate interactions can help navigate these threats and generate multiple ecosystem services. Between 2023 and 2025, as part of technical assistance to Zambia from the UN-REDD Programme, FAO, together with the Polytechnic University of Valencia (UPV) and the University of Zambia (UNZA), led an assessment to understand the forest–water–climate nexus in the forested headwaters of the Zambezi River in five districts of Zambia's Northwestern Province.

Figure G. *Area of assessment showing the pilot area*



Note: Please refer to the disclaimer on page ii for the names and boundaries used in this map.

Sources: Authors' own elaboration based on: Lehner, B. & Grill, G. 2013. Global river hydrography and network routing: baseline data and new approaches to study the world's large river systems. *Hydrological Processes*, 27(15): 2171–2186. https://doi.org/10.1002/hyp.9740; using data from HydroSHEDS. 2025. HydroSHEDS. [Accessed on 7 November 2025]. https://www.hydrosheds.org. ®HydroSHEDS

The analysis included a detailed assessment (pilot area in **Figure G**) of the relationships between forests, water and climate in a small catchment, Ntambu, in the headwaters of the Zambezi River. This was done through the development of several forest management simulations using an adapted version of the ecohydrological model MEDFATE in combination with biophysical and socioeconomic data, as well as drone imagery. Simulations ranged from business-as-usual (the closest scenario to deforestation) to strict conservation and various options for thinning. The methodology and results were developed and shared with a range of stakeholders, including farming communities organized in community forest management groups, representatives from government agencies responsible

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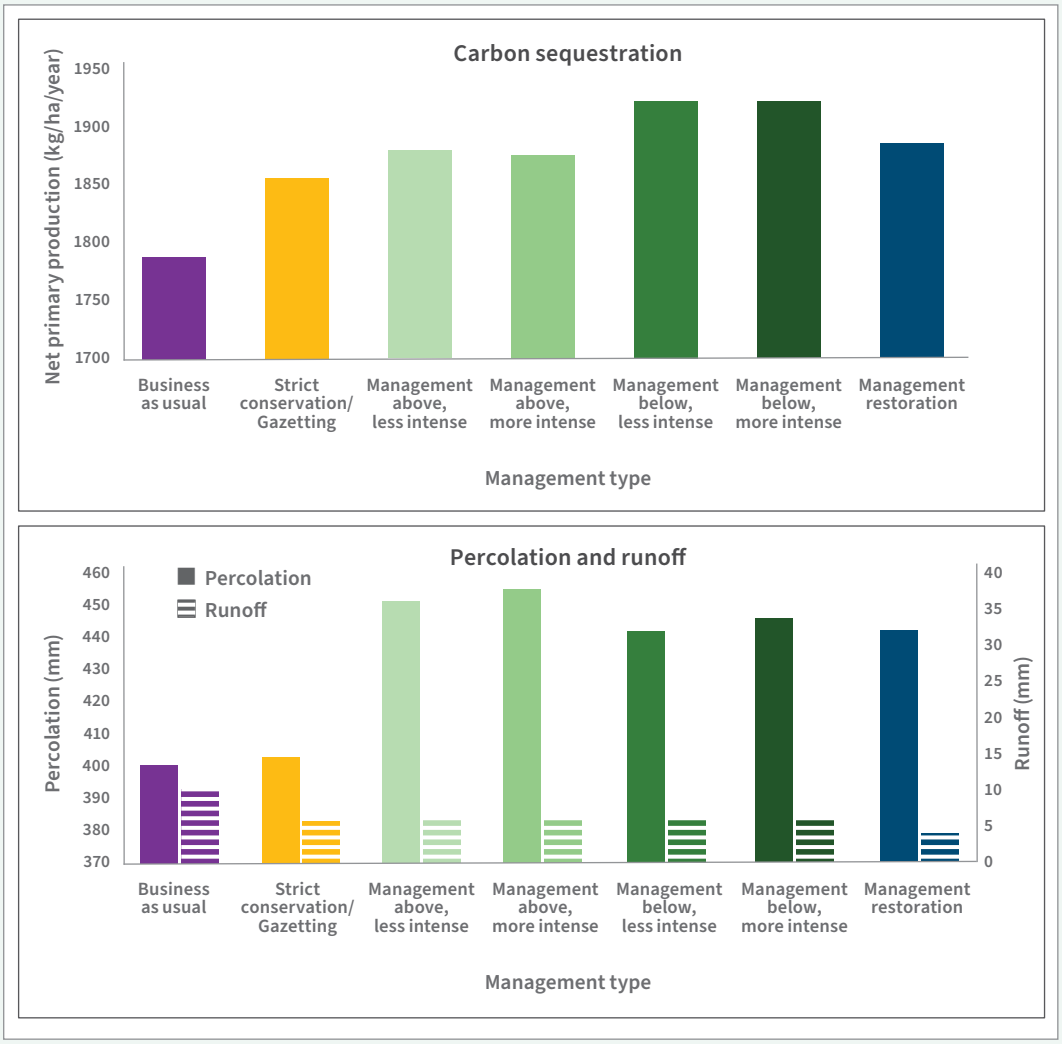
for forestry, water, meteorology, hydropower and agriculture, as well as members of academia and civil society organizations (CSOs). The analysis illustrated how forest management interventions can affect water availability and regulation and climate change mitigation and adaptation, contributing to food and water security.

Results: The study showed that sustainable forest management (green bars in **Figure H**) can improve water availability and regulation. It increases the amount of blue water (water found in rivers, lakes and aquifers) by increasing percolation, which recharges groundwater and creates a more consistent water supply, and by reducing runoff, which lowers erosion and flood risks. Sustainable forest management also contributes to climate change mitigation by increasing carbon sequestration, the extent of which depends on the preferred interventions as seen by the different green bars in **Figure H**. In terms of restoration through reforestation, the results showed that because of the characteristics of the area, special attention needs to be paid to the planting densities and species, as these can decrease percolation and increase fire risk (not shown in **Figure H**). Drone image analysis showed that riparian forests should be prioritized in restoration efforts, as forest loss was observed to be considerable.

Figure H. *Simulated management scenarios and their impact on carbon sequestration (top) and on water (bottom)*



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An increased and well-regulated water supply is particularly important for local communities as their main economic activity is agriculture. In a socioeconomic survey, the communities emphasized water use for livestock and fishing, indicating the importance of the river for food security and local livelihoods. The forests also provide many non-wood forest products, such as honey, wild fruits and vegetables, and mushrooms that are vital for the communities' own consumption and livelihoods. The Integrated Food Security Phase Classification (IPC) for 2023–2025, when the assessment was done, showed that Zambia faced high levels of acute food insecurity (with most districts classified in the "crisis" phase). This is attributed to dry spells leading to droughts, pest infestations and diseases. This makes sustainable forest management in the headwaters more necessary than ever, to regulate the water cycle, sequester carbon, reduce fire risk and provide non-wood forest products, thus contributing to local water and food security in Zambia.

Key takeaways:

- The headwater forests of the Zambezi River are essential for water provision and regulation, and climate change mitigation and adaptation, which contribute to food security.
- Sustainable forest management, especially led by communities, can help leverage forest–water–climate interactions to generate multiple ecosystem services, including agricultural production.
- Multisectoral collaboration is essential to understand forest–water linkages, align management objectives, and plan interventions that maximize ecosystem benefits while minimizing trade-offs, with decision-support system tools serving as effective platforms for bringing actors together and deepening understanding of these linkages.

Improving local-scale atmospheric moisture (green water flows)

Trees are a fundamental part of the water cycle, controlling how incoming sunlight and rainfall are returned to the atmosphere. By doing so, they strongly impact the local and regional climate (Bonan, 2008; Lawrence *et al.*, 2022). Observational and model-based studies on the changes caused by deforestation have informed much of what we know of the importance of forests for the water cycle locally and regionally. There are a number of forest traits and processes that contribute to their importance in the water cycle. For instance, forests (1) have relatively low albedo (are dark) and absorb much of the incoming solar radiation, which helps drive strong atmospheric convection, that is, the vertical transport of heat and moisture in the atmosphere (Bright *et al.*, 2017); (2) support high evapotranspiration rates through deep root water uptake and evaporation of water captured on their surfaces; and (3) present a rough surface and support strong atmospheric mixing. Thus, forests return a lot of energy and moisture to the atmosphere, thereby cooling the land surface and promoting precipitation (Bright *et al.*, 2017; Ellison, Pokorný and Wild, 2024).

In the process of photosynthesis, trees access soil water commonly from depths of 2 m – particularly in humid mid-latitude and polar regions – to 10 m, or even more in many tropical regions and in dry and seasonally dry areas (Nepstad *et al.*, 1994). Forested areas return more than 50 percent of incoming rainfall to the atmosphere (Mercado-Bettín, Salazar and Villegas, 2017). Thus, they affect atmospheric moisture content, both within and above the forest canopy but also in deforested (agricultural) lands which may be nearby or many kilometres away. They support precipitation locally (as well as regionally and globally) by increasing available moisture and fostering strong convection in the atmosphere

BOX 10

The role of forest restoration

Between 1990 and 2025, 110 million hectares of primary forest were lost globally to deforestation (FAO, 2025), with nearly 45 percent of the remaining tropical forests facing severe threats from agriculture, logging and fire, contributing to forest fragmentation and degradation (Gaisberger *et al*., 2023). Ambitious international and regional initiatives like the Bonn Challenge, the African Forest Landscape Restoration Initiative (AFR100), and the United Nations Decade on Ecosystem Restoration have set forest restoration goals on millions of hectares by 2030, demonstrating growing political commitment to forest and landscape restoration that seeks to enhance ecological functionality and human well-being in degraded forest landscapes.*

Current policies and forest restoration strategies typically prioritize objectives including carbon sequestration, improved water quality, and economic benefits from forest products (Creed and Van Noordwijk, 2018). In contrast, the function of forests as suppliers of atmospheric moisture and the subsequent redistributive consequences for downwind areas receive scant attention (Creed and Van Noordwijk, 2018). Considering the global emphasis on and potential impact of large-scale forest restoration efforts on agriculture in terms of rainfall regulation and cooling benefits, in addition to water quantity, quality and timing, a paradigm shift is needed.

In assessing forest, water and energy cycle interactions, a comprehensive view must integrate both large-scale regional and continental dynamics and smaller-scale catchment-based processes. When forest restoration strategies include the water dimension, they often focus solely on the sub-basin, catchment or "watershed" scale (Bruijnzeel *et al.*, 2023; Van Meerveld and Seibert, 2025; Van Meerveld *et al*., 2021; Wei *et al.*, 2025). This ignores the "*supply-side*" relationships of forest, water and energy cycles that are distinctly regional and continental in character (Ellison, Futter and Bishop, 2012). A singular focus on carbon sequestration at the catchment level, to the exclusion of water and energy cycles, fails to account for how these elements move through landscapes. Since all such catchments are connected via the atmosphere, one must ideally understand these functions and how they have been altered, from their origins (*supply-side* perspective) all the way to their ultimate end in surface waters and eventually the ocean (*demand-side* perspective).

Integrating these foundational principles (positive forest, water and energy cycle synergies and hydrologic cycle relationships from the ground up) is essential to achieving more sustainable (i.e. self-sustaining) restoration outcomes. For instance, while removing forest cover might appear to increase water availability in a very immediate sense at the catchment scale, iterated across time and hydrologic space, it will lead to the outcome that water and hydrologic function are greatly reduced within and across the entire land-based system.

Therefore, planning for forest restoration must be structured to reinforce multiscale patterns. Strategists need to consider how forest, water and energy cycle interactions fit into, interact with and support the larger-scale framework of local, regional and potentially even continental wind and weather patterns. While the catchment scale remains an important unit of management, restoration efforts must plan by considering impacts on the water cycle beyond it.

Continued on next page

Achieving benefits at multiple scales is complex and requires a combination of national policies, clear tenure and local-level conservation, restoration and sustainable management.

In Brazil, under national law, the Amazon and Cerrado regions have a "debt" of native vegetation of 9 million hectares and 6 million hectares respectively (Observatório do Código Florestal, 2024). The restoration of those areas, which is mandatory by law, would be an important first step in regulating energy and hydrological fluxes and decreasing average temperatures. It is imperative, therefore, to support large-scale and integrated reforestation actions throughout the Amazon and Cerrado. Initiatives such as REDD+, which provides funding for conservation and restoration projects with the goal of reducing carbon emissions, and community networks such as the Amazônia Seeds Network and the Xingu Seeds Network, which make available large stocks of native seeds, can provide important financial and logistic support for restoration projects.

Note: For more information, see: https://www.bonnchallenge.org/; https://afr100.org/; https://www.decadeonrestoration.org/
Sources: See full box references at the end of the bibliography section.

(Wright *et al.*, 2017). The increased rainfall may be particularly strong at the beginning of the wet season and during drought years (Lawrence and Vandecar, 2015; Spracklen, Arnold and Taylor, 2012). Trees and forests also cool the area through the transfer of energy from the land surface, via evapotranspiration, to the upper atmosphere (Bright *et al.*, 2017; Duveiller, Hooker and Cescatti, 2018).

How atmospheric moisture and precipitation are impacted locally in a mosaic forest–agricultural landscape is a complex function of many local and non-local factors (reviewed in Lawrence and Vandecar [2015]), including the size of deforested patches and how they interact with larger scale drivers of weather like the prevailing winds. But what is clear is that deforestation can redistribute rainfall and change its variability and seasonality locally (Alves *et al.*, 2017; Costa and Pires, 2010; Khanna *et al.*, 2018) and regionally downwind (Spracklen, Arnold and Taylor, 2012).

Studies in regions with significant deforestation have shown that decreased humidity, increased temperature, and changed rainfall regimes increase plant water stress and decrease crop yield (Leite-Filho *et al.*, 2021), and may contribute to limiting farmers to planting one crop per season (instead of two).

Improving the quality of water used for irrigation (blue water stores and flows)

Forests and trees provide vital ecosystem services that improve the quality of blue water stores and flows by creating a natural infrastructure for water purification (Qiu *et al.*, 2023). In general, reservoirs, rivers and lakes experience significantly lower rates of pollution and sediment yields in areas with sustainably managed forests, compared to deforested or agricultural landscapes. Incorporating trees and forests into agricultural landscapes and maintaining riparian buffer zones (i.e. the trees and forests along watercourses) are key in enhancing the capacity of these ecosystems to improve water quality.

Forests are highly effective in filtering nutrients and pollutants from surface water before reaching water storage and irrigation systems. Forest soils absorb excess nutrients such as nitrates and phosphates, which are commonly introduced into water systems through agricultural runoff. This nutrient uptake helps prevent eutrophication in downstream waterbodies and reduces the likelihood of nutrient contamination in irrigation water. Forests also intercept and degrade organic pollutants, such as pesticides and herbicides, through microbial activity in the soil (Diez, 2010). In addition, the forest floor, a mix of leaf litter,

roots and soil microorganisms, acts as a natural filter that traps and decomposes pollutants. As addressed earlier, trees and forests also enhance infiltration and groundwater recharge, which is vital for maintaining a clean and stable supply of water for irrigation. As precipitation infiltrates forest soils, it undergoes a natural filtration process, removing impurities before the water reaches aquifers.

The quality of water coming from forests is almost always higher than from other land uses where the soil is more exposed and soil structure is degraded. Forests and trees play a critical role in preventing sediment loads in waterbodies by reducing soil erosion (Croke, Hairsine and Fogarty, 1999; Dobre *et al.*, 2022). Forests usually have several layers of dense vegetation and litter cover and only minor areas of exposed soil, where tree roots and vegetation are holding the soil in place, reducing the likelihood of erosion during heavy rainfall or flooding events. Flowing water transports sediments – and often attached pollutants, such as pesticides and heavy metals – into watercourses, where they can not only affect water quality but also contribute to the siltation of reservoirs, irrigation channels, and other water storage infrastructure critical for agricultural production, increasing maintenance costs and reducing storage capacity. Soil structure and aggregation are higher in forests compared to cropland, which contributes to reducing the risk of erosion and resulting sediment yields (Bruijnzeel, 2004; Zhu *et al.*, 2018). Additionally, tree canopies intercept rainfall, reducing the intensity of surface runoff, which further mitigates erosion (Ellison *et al.*, 2017).

The integration of trees into agricultural landscapes, such as through agroforestry systems and riparian buffer zones, can enhance soil health, reduce erosion, and prevent nutrients leaching into waterbodies. Riparian buffer zones are critical in reducing sediments, nutrients and pollutants, before they reach streams, rivers or irrigation reservoirs. As an example, riparian forests have been shown to reduce nitrate concentrations in runoff by up to 80 percent, improving water quality for downstream users, including irrigation systems (Mayer *et al.*, 2007). Riparian trees also help stabilize streambanks, reducing erosion and preventing sediments from entering the water (FAO, IUFRO and USDA, 2021).

A NEW ERA OF DECISION-SUPPORT SYSTEMS

In recent years, several decision-support tools for sustainable land management have been developed, promoting integrated management of trees, forests and water. While many tools address specific ecosystem services, few adopt a holistic approach that considers the trade-offs and synergies linked to the trees and forest–water nexus. Existing decision-support tools that focus on trade-offs between agricultural productivity and ecosystem functions and services often neglect water-related considerations (Debeljak *et al.*, 2019). Similarly, most tools supporting forest and landscape restoration (FLR) focus on restoration of mosaic landscapes that include agricultural areas but also lack integration of water-related risks.

A new generation of tools and models is emerging creating opportunities to enhance the uptake of decision-support systems (DSS) and extend their application across sectors. These tools can bring together actors from diverse disciplines, strengthening understanding of forest–water linkages and enhancing tailored, coordinated landscape-, forest- and water management approaches that maximize synergies and minimize trade-offs (**Box 9**). Examples from the forest sector suite of emerging tools include the Water-Smart Forest and Landscape Restoration Tool (W-FLR Tool), MEDFATE and CAFE (Carbon, Aqua, Fire & Eco-resilience) to name a few (de Cáceres *et al.*, 2023; Pérez-Romero *et al.*, 2025; SIWI, 2025).

MEDFATE (used in the case study shown in **Box 9**) and CAFE help scientists, land and natural resource managers, as well as decision makers better understand and manage forest ecosystems under changing climates. They allow for comparisons of forest and landscape management options and balance multiple goals – such as carbon storage, water availability for agriculture and people, and fire risk reduction – while identifying trade-offs and synergies among ecosystem services (de Cáceres *et al.*, 2023; Pérez-Romero *et al.*, 2025). On the other hand, tools such as the W-FLR Tool, support FLR initiatives by integrating water management and hydrological processes into restoration planning through participatory approaches that enhance resilience and long-term sustainability within target areas such as watersheds.

POTENTIAL IMPLICATIONS FOR GOVERNANCE

There is much evidence that trees and forests impact water quantity, quality and timing, which in turn affect agriculture and food production. Current policies, strategies and approaches tend to overlook the green water resources that are generating around half of all rainfall over land (Mazzucato *et al.*, 2024). A recent report from the Global Commission on the Economics of Water, shows that the poorest 10 percent of the world's population live in areas where almost 70 percent of annual precipitation comes from terrestrial moisture recycling, and that these areas are also often hot spots for deforestation,

BOX 11

The agroforestry parklands of Saponé, Burkina Faso

Agroforestry parklands are the predominant farming system in the Sudano-Sahelian zone of West Africa, covering vast areas of land (Boffa, 1999). In these parklands, mature multipurpose trees are scattered among cultivated areas. Farmers deliberately select, retain and protect trees on their farms and manage them in combination with crops and livestock (Kessler, 1992). Parkland trees provide a wide range of ecosystem services critical for the livelihoods of millions in the region (Sinare and Gordon, 2015).

Located in central Burkina Faso, the agroforestry parklands of Saponé are characterized by open areas with scattered trees dominated by karité *Vitellaria paradoxa* C.F.Gaertn. (shea in English). This is the dominant parkland tree species in semi-arid West Africa (Bayala *et al.*, 2015; Lovett and Haq, 2000), providing many products, including shea butter. The average tree density is about 20 trees/ha, and annual crops such as millet, sorghum, peanut and cowpea are cultivated under and among scattered trees. Agricultural production is small scale, subsistence-oriented and rainfed.

The rainy season extends from April to October, followed by a pronounced dry season from November to March. The mean annual precipitation is 790 mm/year, ranging from 570 mm/year to 1189 mm/year (Bargués-Tobella *et al.*, 2014).

Intermediate tree cover can maximize deep soil water drainage and groundwater recharge. Studies examining the effect of tree cover on groundwater recharge in the agroforestry parklands of Saponé have shown that intermediate tree cover increased deep soil water drainage and groundwater recharge (Ilstedt *et al.*, 2016; Bargués Tobella, 2020). The proportion of annual rainfall percolating down to 1.5 m soil depth was greatest around the edge of the tree canopies and decreased both towards the tree stem and with increasing distance from the canopy edge in the open areas. Therefore, little water was available for groundwater recharge both immediately around tree stems and in the open areas far away from trees.

Under high rainfall intensity events (> 20 mm/day), median deep soil water drainage was 13 times higher in small open areas among trees compared to large open areas (Bargués Tobella, 2020), highlighting the importance of maintaining an appropriate tree cover. Results of a modelling exercise of groundwater recharge as a function of tree cover based on measurements of deep soil water drainage and tree transpiration indicate that groundwater recharge is maximized at an intermediate tree density of around 10 to 20 trees/ha (Ilstedt *et al.*, 2016). **At this optimum tree density for groundwater recharge, annual groundwater recharge is four to six times greater than in treeless conditions**. Increasing tree density beyond the optimum, decreases groundwater recharge, although it remains higher than in a treeless situation up to densities of around 20–60 trees/ha. Various mechanisms explain the observed relationships between tree cover and deep soil water drainage and groundwater recharge.

Trees in agroforestry parklands can increase the topsoil water content available to crops through hydraulic lift. In the parklands of Saponé, Bayala *et al.* (2008) estimated that karité and néré *Parkia biglobosa* (Jacq.) Benth., the two dominant tree species, lifted about 73 L and 247 L per tree per day, respectively. These values represent 60 percent and 32 percent of the amount transpired daily, respectively.

Trees can reduce maximum daily temperatures and increase minimum air humidity. Trees modify microclimates, moderating excessive temperatures above 40 °C and providing longer thermal times (the running total of mean daily temperatures that plants need for their development), reduced

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maximum daily temperatures and increased minimum air humidity. This has been observed with both karité and néré (Bayala *et al.* 2013; Jonsson, Ong and Odongo, 1999). The magnitude of these effects depends on tree species and tree size (Bayala *et al.*, 2014). Trees further reduce incoming solar radiation and can either enhance interception losses or collect rainwater inputs depending on rainfall, rain intensity, tree species and canopy shape (Bayala *et al.*, 2014).

Linking agriculture to the forest–water nexus for food security and local communities. Increased water availability contributes to supporting crop establishment at the onset of the rainy season, and during late rains and dry spells (Bayala *et al.*, 2014). It also promotes better vegetative growth and timely crop maturity (Bayala *et al.*, 2013; Ong *et al.*, 2014).

Trees can improve soil carbon content, which in turn improves the stability of the soil structure, and thus water infiltrability and availability in the crop rooting zone (Bargués Tobella, 2020). This highlights the need to conserve and maintain trees in these areas for their role in improving soil health and water management in the Sahel (Bayala *et al.*, 2014).

Shading under trees influences the performance of C4 plants (cereals); this can be managed through tree density and pruning and replacing these with C3 crops (Bayala and Wallace, 2015). The parkland system is more resilient to risks and shocks because of the buffering effects and mechanisms described here. In addition, the trees produce fruits, nuts and leaves that are rich in micronutrients and vitamins, complementing the starch-based diets that are common in parkland communities.

Trees on farms provide an economic safety net for households by increasing cash income and improving caloric intake, dietary diversity, crop yield and livestock productivity in the drylands of West Africa (Binam *et al.*, 2015, 2017; Sinare and Gordon 2015). However, to sustain these systems, adjustments may be needed in terms of species adapted to current and future climates, plant mixes and densities, and crop placement to facilitate the use of agricultural equipment.

The parkland system has been shown to be highly suitable to the dryland context, at least in the Sahel. For long-term viability, it is necessary to document the local ecological knowledge of this system while also considering scientific knowledge on larger scales.

Sources: See full box references at the end of the bibliography section.

making populations severely affected by hunger even more at risk of precipitation reductions and thus reduced or lost harvests (Mazzucato *et al.*, 2024). Strengthening governance mechanisms is therefore vital for enhancing the water-related benefits of forests for agriculture.

As seen throughout this report, integrated approaches to managing water and land are key to reducing risks, minimizing trade-offs, and enhancing the benefits that forests and trees provide for agriculture. Achieving this requires strong enabling environments that foster cross-sector collaboration among government departments (e.g. water, land, energy, agriculture and environment), civil society, and the private sector, supported by participatory multistakeholder processes (Ingemarsson *et al.*, 2022).

Equally important is integrating local and traditional knowledge into policy, practice and research to strengthen governance and ensure landscape and resource management approaches are grounded in local realities. Initiatives such as Living Labs can foster citizen science, co-learning and experimentation on sustainable management options while also serving as co-learning and knowledge exchange centres for farmers (Ali *et al.*, 2025). Inclusive participation in knowledge co-production and decision-making strengthens

adaptive management, transparency, and forest and water stewardship. Evidence shows that decision-support tools can play a significant role in developing coordinated and informed management strategies that support these efforts (Sun *et al*., 2023).

KNOWLEDGE GAPS

Significant gaps in knowledge and policy persist, particularly regarding green water resources. Comprehensive, high-quality, timely, and publicly available data are essential for effective water governance at all scales and across sectors, ensuring efficiency, equity and environmental sustainability. Still, global water data – especially green water data – remain incomplete and highly fragmented, which risks overlooking a significant component of the hydrological cycle (Mazzucato *et al*., 2024). Addressing this gap presents an opportunity to enhance water-data collection through emerging technologies such as satellite imagery, remote sensing and artificial intelligence, which can improve the accuracy and frequency of monitoring. Local data is also an important gap, which is key for developing tailored landscape and resource management solutions. This poses an opportunity to collaborate with local communities and Indigenous Peoples groups through citizen science.

Standardized methods for monitoring trees and forest–water relationships across different scales are also lacking (Sheil and Bargués Tobella, 2020). The ways in which trees and forests influence water availability are site-specific, shaped by local conditions such as climate, topography, elevation, vegetation cover and land use. More research is needed to fully understand these mechanisms, particularly regarding the extent to which forests influence atmospheric moisture, precipitation patterns, and the impacts of specific tree species and functional traits on hydrological processes. High-resolution models can help capture the spatial and temporal variability of trees and forest–water interactions, particularly in the context of climate change, local land-use practices and socioeconomic factors.

CONCLUSIONS

Trees and forests provide crucial water-related ecosystem services, contributing to freshwater supply, regulating water flows and local climate, mitigating water-related hazards, and enhancing water purification. This chapter presented evidence and options for harnessing these benefits for agriculture at different scales.

The critical interconnections between trees, forests and water – and their implications for water and food security – are increasingly recognized in research, policy and practice. However, green water and the role of the trees and forests–water nexus remain largely overlooked, compared to blue water, in economic and policy assessments, despite their vital role in sustaining natural ecosystems and ensuring water and food security. Opportunities for strengthened governance mechanisms and science-based holistic landscape and resource management options emerge.

A stronger science–policy interface is essential. Policymaking must be informed by the latest scientific findings while considering the complex and integrated elements of the trees and forest–water nexus. Systems thinking and holistic landscape and natural resource management approaches can help navigate potential trade-offs and synergies, ensuring that water, agriculture, and trees and forests are managed in a way that supports long-term sustainability and resilience (Ingemarsson *et al*., 2022). A growing suite of decision-support tools that can be adapted to different forested landscapes and bring multiple actors to the table can support these efforts.

For a sustainable and resilient future, it is essential to recognize the full value of the trees and forest–water nexus, encompassing its economic and ecological significance. This requires a comprehensive assessment of green water resources and their systematic integration into economic and policy analyses. Given their critical role in sustaining natural ecosystems, green water resources must be acknowledged not only for their direct contributions but also for the benefits they provide through trees and forests, particularly in supporting rainfed agriculture.

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CHAPTER 5

Benefits of tropical forests for rural workers

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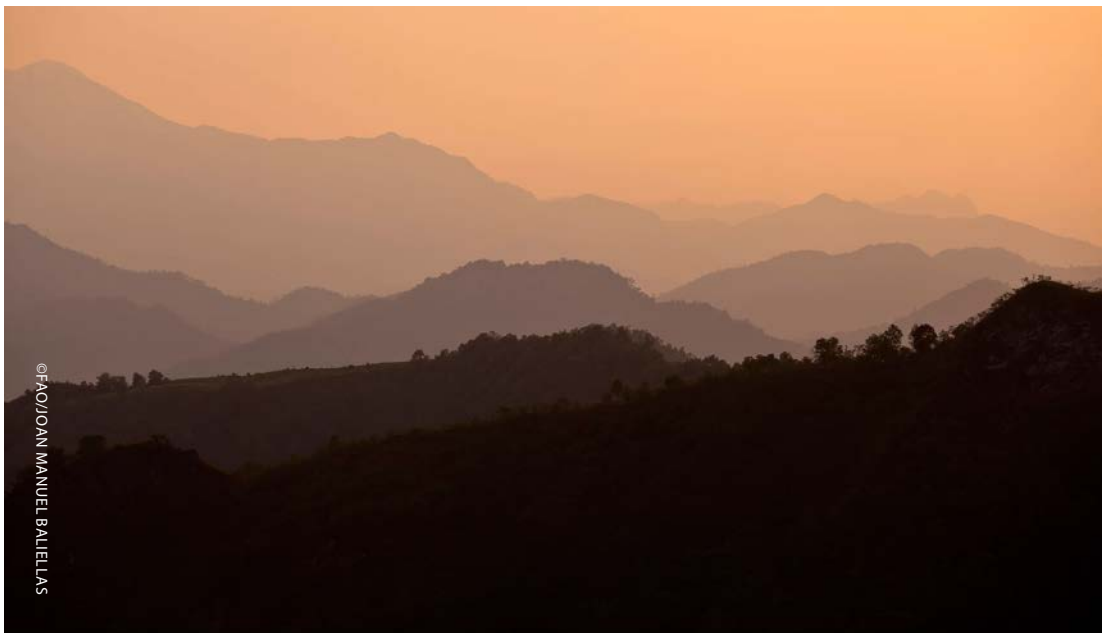
KEY MESSAGES

- **Deforestation drives local warming: Clearing forests removes shade and evaporative cooling, causing land surface temperatures to rise, often by several degrees across tropical regions, and by up to 3–5 °C locally in the Amazon, creating hotter microclimates where people live and work.**
- **Deforestation has human costs: Between 2001 and 2020, tropical deforestation is likely to have contributed to around 28 000 additional heat-related deaths annually, suggesting that forest loss is not just an environmental issue but also a potential public health threat.**
- **Forests are key to adaptation in rural areas: Protecting forests can sustain local cooling, reduce heat-related health risks, and preserve economic productivity, making forest conservation an essential climate adaptation strategy, particularly for rural workers with fewer adaptation options.**

INTRODUCTION

Prior chapters underscore the essential role forests play in regulating temperature across global, regional and local scales. At the global scale, forests act as major carbon sinks, absorbing atmospheric CO_2 and mitigating greenhouse gas-driven warming through biogeochemical processes. At the regional scale, forests sustain evapotranspiration and atmospheric moisture recycling, which impact rainfall patterns and moderate temperature extremes. At the local scale, forests create cooler microclimates through shading, evapotranspiration and canopy roughness, reducing heat stress for crops and rural communities.



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These chapters also highlight how deforestation disrupts these temperature-regulating functions at every scale. Globally, forest loss releases stored carbon, accelerating climate change and amplifying warming trends. Regionally, deforestation reduces evapotranspiration and moisture recycling, delaying the onset of rainy seasons, shortening their duration, and increasing heat extremes in agricultural zones. Locally, clearing forests removes shading and evaporative cooling, causing sharp land surface temperature increases in tropical landscapes.

Building on these insights, this chapter turns to the human dimension of these changes, examining how rising temperatures – driven by both global climate change and local deforestation – affect rural outdoor workers in tropical regions. There are three primary sections in this chapter. The first section reviews the physiological impacts of heat exposure on human health and performance. The second section summarizes the influence of deforestation on local temperature and explores how increased heat exposure from both deforestation and climate change affects rural workers' health, labour productivity and economic well-being. The third section presents adaptation strategies, emphasizing the critical role of forests in reducing heat exposure and strengthening resilience in agricultural communities.

HEAT EXPOSURE EFFECTS ON HUMAN HEALTH AND FUNCTION

Forests help regulate air temperature and reduce human exposure to high daytime temperatures, which is particularly important for those who work outside or indoors with limited climate controls. In this section, we discuss the physiological basis for the link between heat exposure and health.

Physiological impacts of heat

Heat exposure triggers a series of human physiological responses aimed at maintaining a stable internal body temperature. The primary mechanisms for heat dissipation involve increasing blood flow to the skin (via vasodilation) and sweating, which allows heat to transfer to the environment through evaporative cooling (Ebi *et al.*, 2021). However, these thermoregulatory processes can place significant strain on the body, leading to a range of adverse health outcomes (**Figure 6**).

One of the key physiological impacts of heat is increased cardiac demand. As blood vessels dilate to enhance heat transfer, the heart is required to pump harder to maintain adequate circulation. For individuals with underlying heart problems, increased demands on the heart to pump blood can result in cardiac ischaemia (inadequate blood and oxygen delivered to the heart), infarction

(inadequate blood and oxygen causes heart muscle damage or death by heart attack), or collapse (Ebi *et al*., 2021). Dehydration, a common consequence of prolonged heat exposure, further reduces blood volume, compounding the stress on the cardiovascular system. Heat stress can lead to severe outcomes, including heat stroke, which occurs when the body's thermoregulatory mechanisms fail to prevent a dangerous rise in core body temperature (Sawka *et al*., 2011). Individuals with underlying medical conditions such as cardiopulmonary (heart and lung) disease and diabetes mellitus, and those with reduced abilities to thermoregulate or seek access to cooling resources, such as the elderly and very young children, are at particularly high risk. In addition, even healthy individuals such as workers and athletes are at risk of exertional heat stroke during physical activity in the heat (**Figure 6**) (Sawka *et al*., 2011).

Heat also impacts other organ systems. Dehydration, exacerbated by heat exposure, increases the risk of acute kidney injury by reducing blood flow to the kidneys. Chronic kidney disease may also be linked to repeated, prolonged heat exposure and dehydration among outdoor workers (Lunyera *et al*., 2016; Redmon *et al*., 2021). The respiratory system is also affected, as heat can exacerbate pulmonary stress and worsen conditions such as chronic obstructive pulmonary disease (COPD) (Ebi *et al*., 2021). Additionally, heat exposure

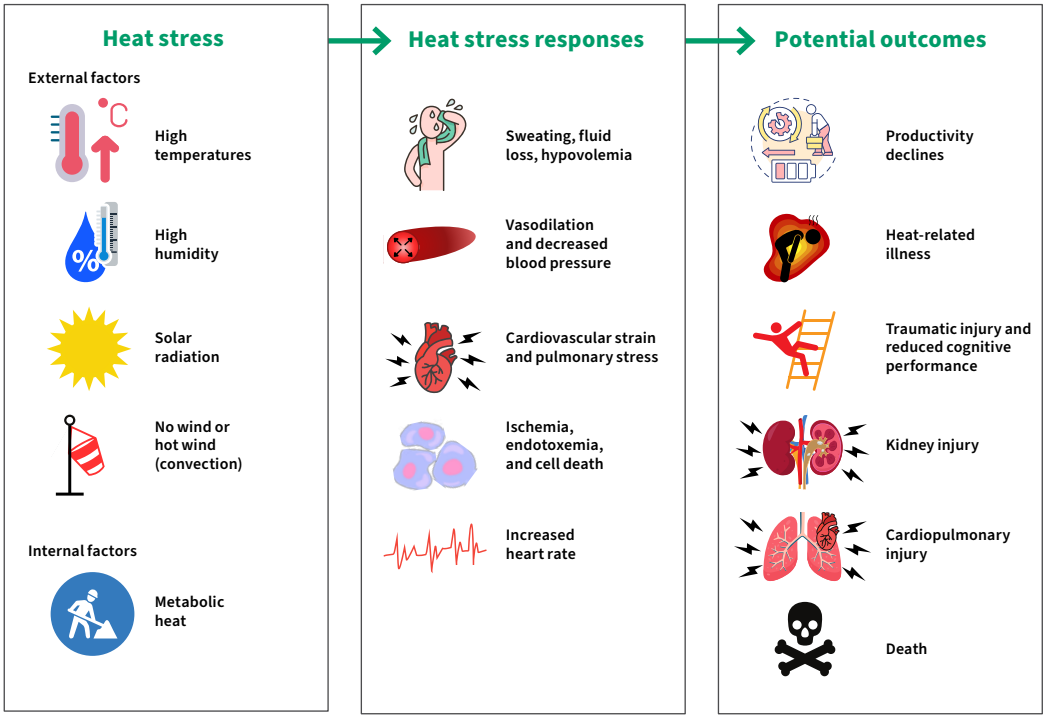
can impair cognitive and motor functions and cause fatigue, reduced concentration, and changes in balance and behaviour. These effects contribute to the increased risk of traumatic injuries, particularly among workers performing physically demanding tasks (Ebi *et al.*, 2021; Masuda *et al.*, 2020; Spector *et al.*, 2019).

In extreme cases, heat exposure can cause irreversible damage to multiple organs. Severe heat stroke has been associated with lasting impairments to the brain, heart, kidneys, liver, gastrointestinal tract and lungs (**Figure 6**). Survivors of heat stroke may face an elevated risk of subsequent mortality due to complications from multiorgan damage (Foster *et al.*, 2021). These long-term consequences underscore the importance of addressing the physiological impacts of heat, particularly for populations most vulnerable to extreme temperatures.

Heat exposure can restrict physical activity due to physiological constraints

Heat exposure can significantly limit physical exertion, reduce work capacity, and diminish productivity, particularly in labour-intensive occupations, such as agriculture, construction and fisheries. The physiological and cognitive mechanisms underlying these reductions are well established. Because the body prioritizes thermoregulation in high temperatures by redirecting blood flow to the skin for heat dissipation, the blood supply to working muscles is reduced, impairing their ability to sustain physical activity. The cardiovascular strain associated with heat exposure contributes to the body's natural tendency to lower the intensity or pace of work in the heat (**Figure 6**), especially during prolonged periods of exertion (Masuda *et al.*, 2021; Sawka, Cheuvront and Kenefick, 2012).

Figure 6. *Mechanisms of heat stress impact on health and well-being outcomes*



Notes: This figure shows the multiple components of heat stress, the channels through which it impacts the human body, and the outcomes that can emerge. Heat stress responses include normal physiological responses to maintain thermal equilibrium, which, when overwhelmed, can lead to tissue damage. Potential outcomes include both acute and long-term effects. Long-term effects may result from high-severity acute effects (e.g. severe heat stroke can lead to long-term organ damage; severe traumatic injury can lead to permanent impairment) or through repeated excess heat exposure incidences (e.g. repeated kidney injury could contribute to chronic kidney disease).

Source: Modified from: Masuda, Y.J., Parsons, L.A., Spector, J.T., Battisti, D.S., Castro, B., Erbaugh, J.T., Game, E.T. *et al.*, 2024. Impacts of warming on outdoor worker well-being in the tropics and adaptation options. *One Earth*, 7(3): 382–400. https://doi.org/10.1016/j.oneear.2024.02.001

The dehydration often accompanying heat exposure compounds these effects by reducing blood volume. This blood volume reduction limits the heart's ability to supply oxygen to muscles and other tissues, leading to earlier onset of fatigue, reduced endurance and physical capacity, slower recovery times, and increased risk of heat-related illnesses, such as heat exhaustion or heat stroke. Additionally, long-term impacts of chronic dehydration in the heat exposure settings – such as kidney damage – can further diminish work capacity over time (Lunyera *et al.*, 2016; Redmon *et al.*, 2021) .

Cognitive and motor impairments caused by heat exacerbate productivity losses. These heat-induced impairments negatively affect decision-making, concentration and coordination, which are critical for maintaining efficiency and safety in the workplace. For example, outdoor workers operating heavy machinery or performing construction tasks are at a heightened risk of accidents due to slower reaction times and impaired judgment (Masuda *et al.*, 2020). These cognitive impacts are particularly concerning for industries requiring precision and skilled motor performance, as errors can have severe consequences, both for worker safety and overall productivity.

Laboratory studies have quantified the effects of heat on physical work capacity. Under mild heat stress, physical work capacity decreases by approximately 10 percent. However, under extreme heat conditions, reductions in capacity can reach as high as 78 percent (ACGIH, 2023; d'Ambrosio Alfano *et al.*, 2014; Foster *et al.*, 2021; Jacklitsch *et al.*, 2016). These findings highlight the non-linear relationship between heat exposure and productivity loss, with severe declines occurring rapidly at higher levels of environmental heat stress. Long-term impairments further exacerbate these losses, as workers with permanent impairment from heat-related injuries have a reduced ability to engage in physical labour (**Figure 6**).

Estimating human heat stress

Accurately estimating heat exposure requires reliable and standardized exposure metrics to guide health and safety recommendations and interventions. Heat stress metrics often incorporate several meteorological factors – such as air temperature, humidity, wind speed and solar radiation – combined with assumptions about clothing, activity levels and acclimatization (physiological adaptation) to heat – to assess potential thresholds of exposure that could result in health effects of heat stress. Metrics that assess thermal comfort and stress may also incorporate assumptions about factors such as age and sweat rate. Below (**Table 8**), we provide an overview of several commonly used environmental heat stress metrics, detailing their definition, thresholds, usefulness and limitations.

The diversity of heat exposure metrics (see a more comprehensive, but not all-inclusive, list and description of heat stress metrics in Buzan, Oleson and Huber [2015]) reflects the complexity of assessing thermal stress in real-world environments (**Table 8**). Although wet bulb globe temperature (WBGT) is often used in occupational health, the military, and sports settings, Heat Index (HI) (in the United States of America) and dry bulb temperature are often more broadly recognized by the public and used in public health and epidemiology studies. However, limitations in existing metrics, such as their reliance on laboratory data and lack of data from regions where individuals are more likely to be heat-acclimatized to calculate recommended levels of safe exposure, underscore the need for more field-based and context-specific research. Developing harmonized, field-validated guidelines that reflect regional variability and work intensity is essential. This includes integrating real-world data from tropical agricultural settings and accounting for physiological limits under heat stress. Without such improvements, current metrics risk underestimating (or overestimating) the danger to agricultural workers, leaving them

vulnerable to heat-related illness, injury and productivity losses in a warming world. Despite a need for refined environmental heat stress metrics, a variety of studies show that there is substantial and growing potential environmental heat stress across many low-elevation areas throughout the tropics (Masuda *et al.*, 2024; Vargas Zeppetello *et al.*, 2022).

Table 8. *Human heat stress metrics*

METRIC	DEFINITION	THRESHOLDS	WHY IT IS USEFUL	LIMITATIONS
Dry bulb temperature (Ta)	Ambient air temperature measured by a standard thermometer in the shade. Widely used in weather reporting and climate studies.	Alone, may not fully capture heat stress risk but can trigger preventive actions. For example, ACGIH recommends workplace evaluation at 27 °C (80 °F) dry bulb temperature or Heat Index.	Easily accessible from most weather stations. Forms the basis for exposure assessment in epidemiological studies linking temperature to health outcomes.	Does not account for humidity, wind speed or solar radiation. Does not fully reflect how the body perceives heat.
Wet bulb temperature (Tw)	Temperature recorded when a thermometer bulb is covered with a wet cloth, reflecting cooling from evaporation. Used by climate scientists to study extreme humid heat. Less commonly used as a stand-alone metric in occupational health.	A Tw above 35 °C is theorized to be the threshold beyond which heat stress becomes unsurvivable, though this threshold can vary with acclimatization, age, sweat rate and activity level.	Accounts for humidity's role in heat stress better than air temperature alone.	Uncompensable heat stress can occur below 35 °C Tw. Studies often lack data from acclimatized tropical populations, creating a research gap. Less straightforward to measure than dry bulb temperature.
Heat Index (HI)	Combines air temperature and relative humidity to estimate how hot it feels. A similar metric, Humidex, used in Canada, uses dew point instead of relative humidity.	US National Weather Service categories: • Caution: HI of 27–32 °C (80–90 °F) may cause fatigue. • Extreme Danger: HI above 54 °C (130 °F) indicates high heat-stroke risk.	Effects of extreme heat on rural workers' health and well-being	Relationship between nutrient cycling, biocontrol, pollination, and others, and crop productivity and resilience
Wet bulb globe temperature (WBGT)	Weighted average of Ta, Tw and black globe temperature (Tb). Tb assesses radiant heat from sunlight or other sources. WBGT includes effects of air temperature, humidity, wind, and solar radiation.	For acclimatized individuals conducting moderate work, NIOSH recommends a WBGT threshold of 28 °C (82.4 °F) with regular breaks. For heavy work, thresholds are lower, e.g. 25–26 °C WBGT, varying by work intensity, breaks, acclimatization and clothing.	Particularly valuable for occupational health and safety because it integrates multiple environmental factors relevant for heat stress. Basis for many health and safety guidelines, including those from ISO, NIOSH and ACGIH.	Thresholds often derived from temperate-climate laboratory studies, raising questions about relevance for tropical regions. Measurement requires specialized equipment for accuracy. WBGT estimates from weather model data are less precise.

Notes: ACGIH, American Conference of Governmental Industrial Hygienists; ISO, International Organization for Standardization; NIOSH, National Institute for Occupational Safety and Health.

IMPACT OF DEFORESTATION AND CLIMATE CHANGE ON RURAL WORKERS

Deforestation patch size influences local temperature

Deforestation significantly influences local temperature dynamics as forest cover plays a critical role in regulating heat through shading and evapotranspiration. The removal of forests disrupts these natural cooling mechanisms, usually leading to substantial increases in land surface temperatures. Studies indicate that deforestation can raise local daytime land surface temperatures by several degrees Celsius, with the magnitude of warming depending on the size and configuration of deforested patches (Lawrence *et al*., 2022; Masuda *et al*., 2019; Vargas Zeppetello *et al*., 2020).

Smaller deforested patches, particularly those surrounded by forest, experience less warming likely due to the moderating influence of adjacent tree cover and atmospheric mixing (**Chapter 4**). However, as deforested patches become larger and more contiguous, the buffering capacity of nearby forests diminishes, exacerbating local heat stress. The largest temperature increases in non-urban tropical environments occur after large, contiguous patches of forests are cleared. When forests are cleared over extensive regions, the loss of tree cover eliminates the shading effect over a wide area, which alters the water availability near the surface; if these ecosystems lose their capacity for evaporative cooling, more heat is retained at the surface. One remote sensing study in the Amazon finds that large-scale deforestation for agricultural expansion has led to local land surface temperature increases of up to 3–5 °C (Vargas Zeppetello *et al*., 2020).

The effects of deforestation on temperature are not limited to the immediate area. Just as the warming within smaller deforested patches is moderated by surrounding forest, the converse has also been observed, with temperature increases from large clearings extending tens of kilometres beyond deforested regions due to changes in land–atmosphere interactions (Cohn *et al*., 2019; Crompton *et al*., 2021).

Efforts to reduce the temperature impacts of deforestation have focused on reforestation and afforestation programmes, as well as policies to limit forest clearance. For example, Indonesia's

moratorium on forest clearing for agricultural expansion successfully reduced deforestation rates, highlighting the potential for policy interventions to counteract local temperature increases (Chen, Kennedy and Xu, 2019). However, the effectiveness of these measures depends on enforcement and the willingness of stakeholders to adopt sustainable land-use practices.

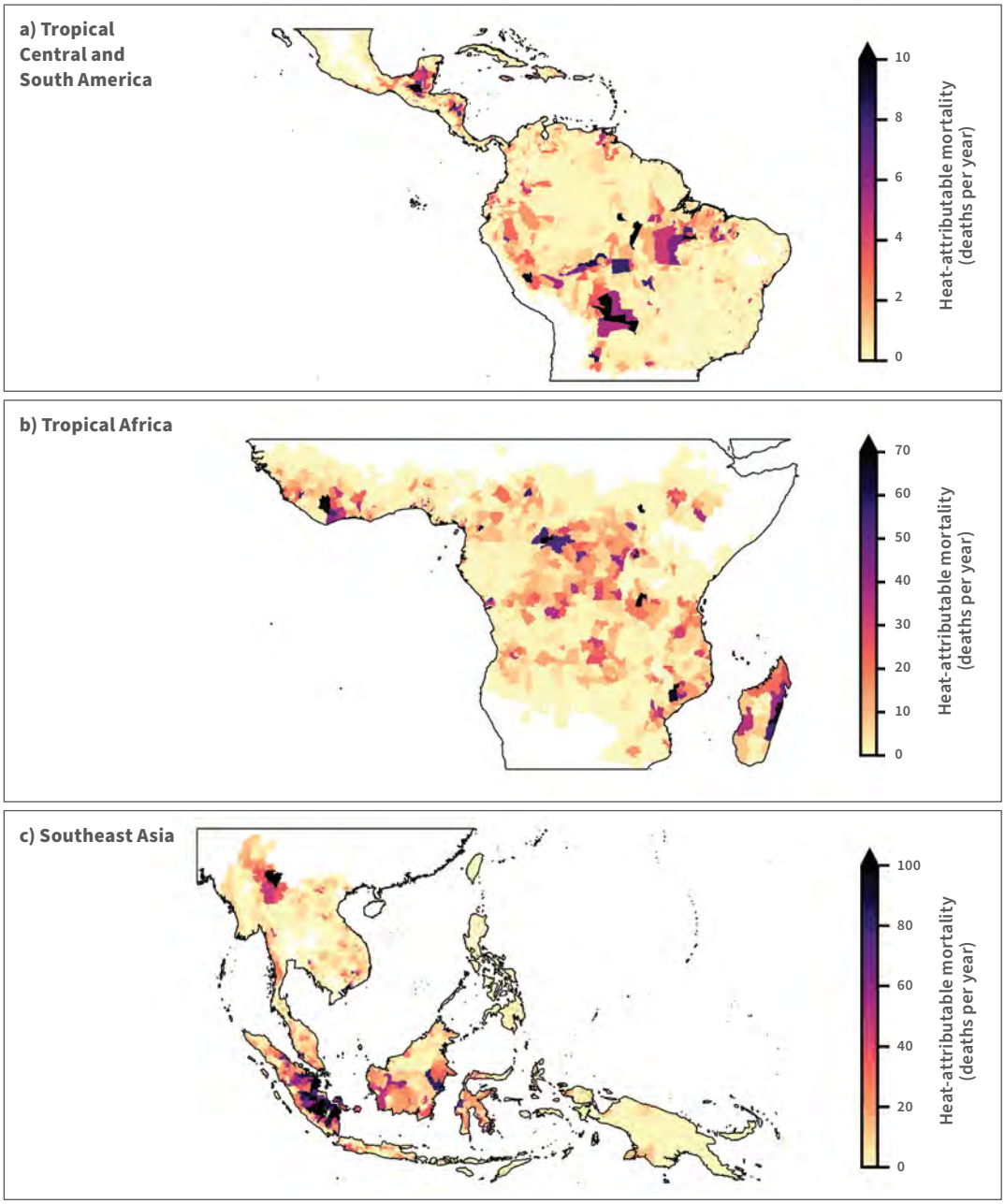
Complementing these safeguards, agroforestry systems sequester carbon and deliver rural co-benefits while also providing measurable cooling services. Recent evidence shows that trees in pasturelands (silvopasture) across Latin America and Africa offer substantial cooling that scales linearly by -0.32 °C to -2.4 °C per 10 tonnes of woody carbon per hectare. Importantly, these cooling benefits do not depend on the spatial extent of the silvopasture systems – so even smallholders can realize significant cooling benefits (Vargas Zeppetello *et al*., 2022). Mapping realistic (but ambitious) silvopasture expansion indicates these systems could counteract a substantial fraction of projected local warming from global climate change by 2050, identifying where and to what extent tree-based practices can help vulnerable communities adapt to a warming world (Vargas Zeppetello *et al*., 2022). Together, strong enforcement of anti-deforestation policies and targeted expansion of agroforestry and silvopasture create mutually reinforcing pathways to limit warming from forest loss while cooling working landscapes.

Impacts of deforestation and climate change on health, labour and the economy

Deforestation and climate change can both significantly impact health, labour and economic productivity, particularly in tropical regions. A recent modelling study (Reddington *et al*., 2025) estimated heat-related excess mortality from deforestation by combining deforestation-related temperature changes with region-specific heat vulnerability indices (Lee *et al*., 2019) and non-accidental mortality rates (Murray *et al*., 2020). This modelling study estimated that between 2001 and 2020, deforestation alone was associated with an average land surface temperature increase of 0.45 °C across the tropics, with regional averages of 0.53 °C in tropical Central and South America, 0.39 °C in tropical Africa and 0.39 °C in Southeast Asia. Because deforested areas with stronger warming tend to be in more sparsely populated rural areas, population-weighted increases in land surface temperature associated with deforestation were lower than area-based estimates, with values of 0.27 °C for the tropics overall, 0.32 °C for tropical Africa, 0.26 °C for Southeast Asia and 0.22 °C for tropical Central and South America (Reddington *et al*., 2025). When compared to the local warming from global climate change over this time period (2001–2020), the modelling study estimated that deforestation contributed 64 percent of total local warming.

Reddington *et al.* (2025) highlight the sobering impact of deforestation-induced warming when combining mortality rate with population data to estimate heat-attributable excess deaths (**Figure 7**). They estimate that warming from deforestation between 2001 and 2020 caused an additional 28 330 deaths annually (95-percent CI: 23 610–33 560) across tropical regions affected by forest loss (**Table 9**). Regionally, Southeast Asia experienced the highest mortality burden with 15 680 (CI: 13 000–18 470) annual excess deaths, driven by a relatively large, exposed population with higher heat vulnerability. Tropical Africa experienced 9 890 (CI: 8 250–11 850) annual excess deaths, lower than Southeast Asia despite greater population exposure due to assumed lower heat vulnerability. Tropical Central and South America saw the lowest mortality burden with 2 520 (CI: 2 160–2 950) annual excess deaths, largely due to the relatively low population density in areas affected by deforestation-induced warming despite experiencing some of the highest magnitudes of warming. On a country-specific level, the highest modelled mortality burdens were found in Indonesia (6 730 deaths/year), Malaysia (2 100), Viet Nam (2 020), the Democratic Republic of the Congo (1 840), the Philippines (1 740) and Nigeria (1 310) (**Table 9**).

Figure 7. *Heat-related non-accidental mortality associated with deforestation-induced warming*



Notes: Refer to the disclaimer on page ii for the names and boundaries used in this map.
a–c, The maps show regions of tropical Central and South America (a), tropical Africa (b) and Southeast Asia (c). The colours show the number of deaths per year (central estimate) for populations located in areas of forest loss, aggregated by second-level administrative divisions (boundaries from GADM, https://gadm.org/index.html). Note that the colour scales are different for each region. The administrative divisions containing no data points are shown in white.

Source: Reddington, C.L., Smith, C., Butt, E.W., Baker, J.C.A., Oliveira, B.F.A., Yamba, E.I. & Spracklen, D.V. 2025. Tropical deforestation is associated with considerable heat-related mortality. *Nature Climate Change*, 15(9): 992–999. https://doi.org/10.1038/s41558-025-02411-0

Notably, the study finds the impacts of deforestation-induced warming are comparable to other major health effects, such as smoke pollution from fires and malaria, highlighting how increasing local temperatures from tropical deforestation warrant serious consideration.

Although the potential loss of life from deforestation-related local warming has profound and devastating effects on individuals and their families, the broader economic and societal consequences of modelled labour lost to heat exposure are likely even more far-reaching.

For example, a 2021 modelling study estimated the potential local warming associated with tropical deforestation as well as its potential impacts on safe outdoor working conditions across 94 low-latitude countries (Parsons *et al.*, 2021). Temperature increases between 2003 and 2018 in deforested areas were associated with 4.9 million people losing more than 0.5 hours per

Table 9. *Population exposure to local land surface temperature increases associated with deforestation between 2001 and 2020, and the associated heat-related non-accidental mortality burden*

REGION/COUNTRY	POPULATION IN LOCATIONS OF FOREST LOSS	POPULATION EXPOSED TO DEFORESTATION-INDUCED WARMING	ANNUAL DEFORESTATION-ASSOCIATED HEAT-RELATED MORTALITY	ANNUAL DEFORESTATION-ASSOCIATED HEAT-RELATED MORTALITY RATE (DEATHS PER 100 000 PEOPLE)	PERCENTAGE OF TOTAL HEAT-RELATED MORTALITY	PERCENTAGE OF TOTAL NON-ACCIDENTAL MORTALITY
Tropics (25°S to 25°N)	452 million	345 million (76%)	28 230 (23 610–33 560)	6 (5–7)	39.1%	1.06%
Tropical Central and South America	89.8 million	66.9 million (74%)	2 520 (2 160–2 950)	3 (2–3)	43.5%	0.55%
Tropical Africa	185 million	148 million (80%)	9 890 (8 250–11 850)	5 (4–6)	35.2%	0.85%
Southeast Asia	165 million	122 million (74%)	15 680 (13 000–18 470)	10 (8–11)	42.4%	1.60%
Indonesia	62.9 million	48.9 million (78%)	6 730 (5 540–7 930)	14 (11–16)	46.4%	0.41%
Malaysia	17.5 million	15.3 million (88%)	2 120 (1 680–2 550)	14 (11–17)	37.3%	1.26%
Viet Nam	10.9 million	6.95 million (64%)	2 020 (1 730–2 310)	29 (25–33)	52.0%	0.35%
Democratic Republic of the Congo	51.0 million	42.0 million (82%)	1 840 (1 530–2 190)	4 (4–5)	34.0%	0.31%
Philippines	16.9 million	13.9 million (82%)	1 740 (1 490–2 010)	13 (11–14)	30.9%	0.31%
Nigeria	21.0 million	17.2 million (82%)	1 310 (1 090–1 570)	8 (6–9)	23.1%	0.09%
Mozambique	8.98 million	8.03 million (89%)	1 020 (870–1 230)	13 (11–14)	50.3%	0.47%
Brazil	30.7 million	21.6 million (70%)	990 (890–1 100)	5 (4–5)	38.6%	0.09%
United Republic of Tanzania	9.35 million	8.03 million (86%)	800 (670–930)	10 (9–12)	107.0%	0.23%
Uganda	11.5 million	9.17 million (80%)	650 (560–770)	7 (6–8)	37.0%	0.27%

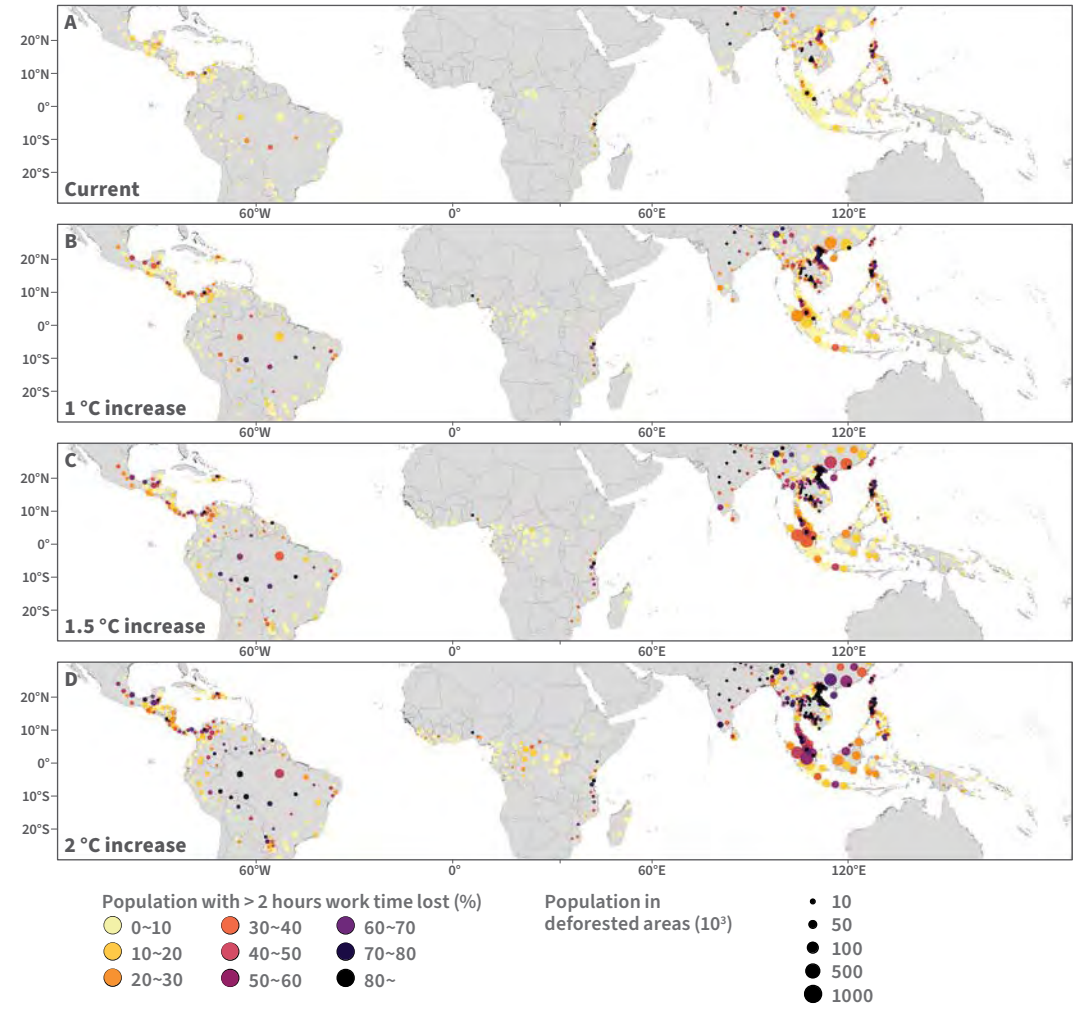
Notes: The results are shown for populations located in areas of forest loss only, aggregated for the whole tropics, for the three main tropical forest regions and for the ten countries with the greatest deforestation-associated heat-related mortality burdens. All regions are bounded by latitudes of 25° south and 25° north. Populations are only counted in forest loss pixels with valid ΔT data and a net forest extent increase of < 50 percentage points. Mortality burdens are shown to the nearest ten for the total mortality and nearest whole number for the mortality rate. The uncertainty ranges are shown in parentheses and are estimated using the 95-percent CI from the non-accidental mortality rates (Murray *et al.*, 2020). Note that deforestation-associated heat-related deaths in a region can exceed the number of total heat-related deaths in that region where surrounding non-deforested areas experience an overall cooling (see methods in Reddington *et al.* [2025]).

Sources: Murray, C.J.L., Aravkin, A.Y., Zheng, P., Abbafati, C., Abbas, K.M., Abbasi-Kangevari, M., Abd-Allah, F. *et al.*, 2020. Global burden of 87 risk factors in 204 countries and territories, 1990–2019: a systematic analysis for the Global Burden of Disease Study 2019. *The Lancet*, 396(10258): 1223–1249. https://doi.org/10.1016/S0140-6736(20)30752-2; Reddington, C.L., Smith, C., Butt, E.W., Baker, J.C.A., Oliveira, B.F.A., Yamba, E.I. & Spracklen, D.V. 2025. Tropical deforestation is associated with considerable heat-related mortality. *Nature Climate Change*, 15(9): 992–999. https://doi.org/10.1038/s41558-025-02411-0

day of safe work time, with 91 000 people losing more than 2 hours per day. By analysing outdoor worker statistics across 41 countries, researchers found that deforested areas had significantly higher proportions of affected workers compared to areas that maintained forest cover. Specifically, among outdoor workers in deforested areas, 7.9 percent in the Americas, 4.3 percent in Africa, and 10.8 percent in Asia lost at least 0.5 hours of safe work time daily (Parsons *et al.*, 2021). In total, over 2.8 million outdoor workers across these regions experienced deforestation-related losses in safe work hours. By contrast, in areas that kept their forest cover, only 1.24 percent of outdoor workers in the Americas, 0.16 percent in Africa, and 2.79 percent in Asia experienced similar losses in modelled safe work hours.

Future global warming will intensify the heat exposure impacts already associated with deforestation (**Figure 8**). With global temperature increases of +1 °C, +1.5 °C and +2 °C beyond 2018 levels, the number of people in recently deforested areas

Figure 8. *Population in deforested areas with greater than 2 hours of work time lost currently and with additional global warming (A–D)*



Notes: Refer to the disclaimer on page ii for the names and boundaries used in this map. Final boundary between the Republic of Sudan and the Republic of South Sudan has not yet been determined. Final status of the Abyei area is not yet determined. Percent of population living in deforested areas exposed to > 2 hours of safe work time lost in deforested areas in 2018 (A) and with an additional 1 °C (B), 1.5 °C (C), and 2 °C (D) of global warming relative to the recent past, assuming no further deforestation or population change. The circle sizes on the maps increase with higher total population, and darker colours of circles correspond to increased percent of population exposed to > 2 hours of safe work time lost per day.

Source: Parsons, L.A., Jung, J., Masuda, Y.J., Vargas Zeppetello, L.R., Wolff, N.H., Kroeger, T., Battisti, D.S. & Spector, J.T. 2021. Tropical deforestation accelerates local warming and loss of safe outdoor working hours. *One Earth*, 4(12): 1730–1740. https://doi.org/10.1016/j.oneear.2021.11.016

losing 0.5 hours of safe work time daily could increase by 5, 6.5 and 7.7 million people, respectively (Parsons *et al*., 2021). More severe impacts (over 2 hours of lost safe work time) will affect an additional 2.8, 5.6 and 9.6 million people (**Figure 8**). These projections represent a conservative baseline, as they assume no further deforestation or population growth.

To date, no studies have quantified the full economic consequences of deforestation's heat-related mortality and productivity losses. Existing evidence on the global economic burden of climate change and rising temperatures provides useful context. Elevated heat is already linked to roughly 490 000 deaths annually (Zhao *et al*., 2021), while productivity losses are valued between several hundred billion and over USD 2 trillion per year (Parsons *et al*., 2022). By 2030, these losses could equal 80–136 million full-time jobs globally, with the greatest per-capita impacts near the equator (Kjellström *et al*., 2019; Romanello *et al*., 2022). In tropical regions, outdoor workers may already lose 650 billion hours of heavy labour annually due to unsafe heat exposure (Parsons *et a*l., 2022), and manual agricultural labourers in half of the world's cropland regions have experienced a 14 percent decline in physical work capacity during growing seasons (Nelson *et al*., 2024). Beyond labour, extreme heat depresses economic output and growth (Bilal and Känzig, 2024; Burke, Hsiang and Miguel, 2015; Callahan and Mankin, 2022; Kotz, Levermann and Wenz, 2024; Tol, 2024), contributing to cumulative global gross domestic product (GDP) losses of USD 5–29.3 trillion between 1992 and 2013 (Callahan and Mankin, 2022) and widening economic disparities (Callahan and Mankin, 2022; Diffenbaugh and Burke, 2019). Further research should examine the economic costs of deforestation, focusing on its interaction with heat-driven labour productivity losses and resulting effects on planting decisions, crop yields, food security, and supply chain stability.

The health impacts of heat further compound these economic losses. Acute heat-related illnesses, such as heat stroke, can result in permanent disabilities, reducing both individual earning potential and workforce participation. Chronic health conditions, including heat-related kidney and cardiovascular disease, place additional burdens on health care systems and reduce the long-term productivity of affected populations. As global temperatures rise, these health and economic impacts are expected to intensify (Cruz and Rossi-Hansberg, 2024; Kotz, Levermann and Wenz, 2024), particularly in tropical regions where workers are already operating at the limits of physiological tolerance.

ADAPTATION STRATEGIES FOR OUTDOOR WORKERS FACING RISING HEAT EXPOSURE IN THE TROPICS

Climate change poses a significant threat to over a billion outdoor workers in the tropics, where modelling studies estimate that nearly a fifth of all hours in the year already exceed recommended safety thresholds for heavy labour (Masuda *et al*., 2024). As global temperatures rise, the challenges for outdoor workers in the agriculture, construction, fisheries and forestry sectors, as well as those engaged in informal household work such as water collection, will continue to intensify, necessitating comprehensive adaptation strategies across multiple scales. While the impacts of heat exposure on human health are increasingly well understood, the ways in which people across the tropics are adapting remain poorly characterized. Policies and practices that foster resilience—rather than maladaptation—have been hindered by a lack of broad, systematic study (Schipper *et al*., 2020). This gap is partly due to the diversity of livelihood strategies, economic conditions, infrastructure, and other contextual factors across tropical regions, which complicate predictions about how adaptation will unfold. However, existing evidence and frameworks provide insights on the type of adaptive actions that have a high likelihood of increasing worker resilience to heat. This section synthesizes current adaptation approaches, their limitations, and potential solutions from Masuda *et al.* (2024), emphasizing the critical role of forest conservation, restoration and landscape-scale management in strengthening adaptive capacity for tropical workers.

Conceptual framework for adaptation

Adaptation to extreme heat spans a spectrum of actions from immediate coping strategies to transformational changes in social and economic systems (Masuda *et al*., 2024). Each step increases the magnitude of local populations' adaptive capacity. At the most basic level, individuals employ **coping strategies** – incremental behaviour changes that help reduce heat exposure and its effects in the moment, such as drinking more water. As heat exposure becomes more common, **adaptation strategies** become necessary – more substantial systemic workplace changes that reduce exposure over time through modification to working patterns, resource management and workplace infrastructure. Here, workers and employers may take on work activities with more opportunities for rest breaks and reduced work pace, change when and what crops are planted to adjust for a changing climate, or install cooling stations and infrastructure to support worker health. In short, the aim is to maintain their primary livelihood strategies even with increasing heat exposure. At the far end of the spectrum lies **transformational adaptation**, which Morrison *et al.* (2022) describe as radical interventions that strategically transform social and economic systems to reduce long-term heat impacts by addressing fundamental vulnerabilities. These may be collective actions that aim to fundamentally change power dynamics in governance, economics and other facets that reorient society, like basic income schemes and other wealth transfers or policy interventions that sustainably protect forests and provide payments to local communities for providing a global public good. These transformations allow workers to increase adaptive capacity and promote resilience by allowing structural changes in decreasing risks of excess heat exposure.

Effective heat adaptation requires coordinated action across different societal levels from individual workers, to companies, to governments. Masuda *et al.* (2024) organize adaptation solutions by the actors who can implement them (government, community/household, employer and individual), and categorize them into three prevention levels borrowed from public health frameworks (Hess *et al*., 2023):

1. **Primary solutions** proactively reduce heat exposure and enhance adaptive capacity before impacts occur.
2. **Secondary solutions** aim to reduce risks during heat exposure events.
3. **Tertiary solutions** mitigate the severity of impacts after heat stress has caused adverse effects.

For example, a primary solution that governments can take is to significantly reduce greenhouse-gas emissions through enhanced efforts that halt and reverse deforestation and forest degradation. Another primary solution could include developing and enforcing more worker-friendly occupational health and safety and labour regulations that include provisions to reduce worker heat stress. Secondary solutions may include public service campaigns to ensure workers are aware of their rights, while tertiary solutions may include providing workers' compensation, and rehabilitative, vocational and financial benefits to workers who have experienced health effects or missed work from heat stress. Actions that utilize forests and trees for increasing adaptive capacity to heat can be thought of as primary and secondary solutions. Efforts that utilize forests and trees can be instituted by governments, companies, communities and individuals. The magnitude of these solutions can vary along the adaptation spectrum but should appropriately aim to increase adaptive capacity, aid in active adaptation, or mitigate impacts that are already present. This multilevel approach recognizes that no single adaptation strategy can fully address the complex challenges posed by increasing heat exposure in tropical regions.

Current adaptation practices and knowledge

Most outdoor workers in the tropics already practice some form of autonomous adaptation – actions taken intuitively within cultural contexts rather than

learned through formal programmes. Castro and Sen (2022) refer to these as "everyday adaptations", which are primarily driven by people's perceptions rather than objective heat exposure measurements (Masuda *et al.*, 2019; Wolff *et al.*, 2018; Zander *et al.*, 2018).

These autonomous strategies include decreasing activities with high heat exposure (Masuda *et al.*, 2019), shifting to new livelihood strategies (Turek-Hankins *et al.*, 2021), increasing reliance on remittances from migrated household members (Gray and Mueller, 2012; Mueller, Gray and Kosec, 2014), increasing labour mobility (Dun *et al.*, 2022), and in extreme cases, relocating entire households (Chazanoël, Mach and Ionesco, 2017). At the individual level, workers may intuitively seek cooler spaces on hot days (Liu *et al.*, 2013) or rotate work tasks to balance the impacts of more strenuous activities (Oppermann *et al.*, 2018).

The majority of documented evidence on adaptation to heat in the tropics comes from agricultural contexts (Turek-Hankins *et al.*, 2021). Farmers have developed various strategies to adapt to changing climate conditions, including: modifying land management practices, irrigation systems, farming calendars, and water harvesting techniques (Chepkoech *et al.*, 2020); shifting the timing of farming activities to avoid the hottest periods; adopting drought-tolerant and early-maturing crop varieties; planting fruit trees to increase shade (Tambo and Abdoulaye, 2013). These agricultural adaptation strategies demonstrate the resourcefulness of tropical communities but may not be sufficient with increasing heat exposure. Evidence on the multiple ways in which households and communities are adapting to heat in the tropics remains undercharacterized.

Constraints and limitations to adaptation

Individual factors such as gender, age and socioeconomic status significantly constrain adaptation options. Studies from Kenya show that men and women often adopt different adaptation strategies aligned with cultural norms – wives more frequently implement crop-related adaptations while husbands focus on livestock and agroforestry interventions (Ngigi, Mueller and Birner, 2017). These differences reflect broader societal patterns where

female farmers typically have better access to social capital, while male farmers more readily access financial capital (Deere and Doss, 2006; Fletschner, Deo and Mhoja, 2022). In many tropical countries, women's adaptation options are further limited by inheritance and land ownership restrictions, preventing them from obtaining loans to diversify into less heat-exposed livelihoods or implement land management practices. Addressing these gender-based disparities is crucial for promoting more equitable adaptation strategies.

Perhaps most concerning is that behavioural adaptations will eventually reach physiological limits as global temperatures rise from climate change (Berrang-Ford *et al.*, 2021) and local and regional temperatures increase from deforestation and urbanization. One key strategy – shifting work to cooler times of day – will become increasingly ineffective (Parsons *et al.*, 2021). Takakura *et al.* (2018) project that by the end of the century, workers would need to shift approximately 5.7 hours from daytime schedules to maintain productivity. However, as Parsons *et al.* (2021) note, even historically cooler early-morning hours can become too hot for continuous strenuous outdoor work in some regions as global warming progresses. The combination of decreased productivity and reduced income from shortened work hours creates a troubling scenario where adaptation strategies themselves reach fundamental limits, highlighting the urgent need for both mitigation and more robust adaptation approaches.

Uneven power dynamics between employers and employees represent another significant constraint. Peckham *et al.* (2017) observe that employers often control the timing and duration of work and breaks and can pressure employees to work longer and at higher intensities using inherent power imbalances and financial incentives. Raising awareness about heat health practices will achieve little if workers fear employment loss, retaliation or impacts to livelihoods for implementing them.

Some adaptation strategies may lead to unintended negative consequences – known as "maladaptation" (Schipper, 2020). For example, increasing reliance on air conditioning may provide immediate relief and allow individuals and households to adapt, but at a societal level, it generates greater energy demand, potentially increasing greenhouse-gas emissions and magnifying long-term global warming (Colelli, Wing and Cian, 2023). Similarly, migration to areas with less heat exposure can introduce new vulnerabilities, with evidence showing that migrants often face reduced livelihood opportunities and heightened social precarity at their destinations (Szaboova *et al.*, 2023).

Comprehensive adaptation solutions

Government-level solutions

Governments have an outsized role in fostering conditions that reduce worker heat stress through multiple channels (Masuda *et al.*, 2024). Less favourable working conditions and limited worker rights among emerging economies present opportunities for governments to increase resilience for workers (ILO, 2025).

Primary solutions:

- Enacting ambitious greenhouse-gas emission reduction targets.
- Implementing policies that reduce deforestation and promote sustainable land use.
- Implementing policies that promote reforestation of degraded land.
- Developing and enforcing occupational health and safety regulations with specific provisions for heat exposure.

Secondary solutions:

- Implementing occupational health and safety regulations for heat stress (e.g. increasing access to shade, more work breaks, allowing flexible working hours).
- Enforcing health response provisions.
- Encouraging public education campaigns on heat stress prevention.

Tertiary solutions:

- Encouraging public campaigns on responding to heat-related symptoms.
- Enacting workers' compensation and vocational benefits.
- Improving health care access.
- Providing employment transition grants for heat-exposed workers.

Importantly, with sufficient political will and public support, government policies can profoundly shape drivers of land-use change that exacerbate heat extremes. For example, agricultural subsidies influence crop and livestock choices, which in turn determine how much land farmers clear for production. Moratoriums on deforestation, such as those implemented in Indonesia, have proven effective at decreasing land conversion (Chen, Kennedy and Xu, 2019), highlighting the importance of government action in addressing this key driver of local heat increase.

Community and household solutions

Communities and households can implement vital adaptation measures that complement individual and governmental efforts. Primary solutions at this level include developing tailored worker heat stress prevention training through community organizations and creating tools that support heat adaptation in different work settings. For landowners or communities with common land, adopting more sustainable land-use plans that maintain forests and trees for their cooling benefits relative to other trade-offs may be important. Secondary solutions focus on training workers and community health professionals to recognize and respond to heat-related illness symptoms. At the tertiary level, communities can provide monetary or in-kind assistance to households with recovering workers and offer support through informal networks or community savings associations to help transition to less heat-exposed livelihoods (Masuda *et al.*, 2024).

Employer-based solutions

Employers control many workplace factors that determine heat exposure. Primary employer solutions include training workers and supervisors on heat-illness recognition and implementing comprehensive occupational heat policies. Secondary measures involve creating flexible work schedules, providing adequate rest breaks, establishing cooling stations, and potentially implementing land-use plans that integrate more trees that provide shade for outdoor workers (Masuda *et al.*, 2024). Tertiary employer solutions focus on accommodating medical restrictions for

workers recovering from heat-related illnesses and providing paid time off and medical assistance when formal workers' compensation is not available.

Individual worker solutions

Although individuals have the least control over broader systemic factors, they can still take meaningful adaptation actions. Primary solutions include following heat stress-prevention best practices such as wearing appropriate clothing and maintaining adequate hydration. For individual landowners with working lands, this may mean integrating trees or maintaining forests where appropriate. Secondary solutions involve implementing proper procedures for identifying and reporting heat stress symptoms in themselves and co-workers. At the tertiary level, individuals may pursue opportunities to shift to less heat-exposed livelihood strategies when possible (Masuda *et al*., 2024).

Extending adaptation limits

Several approaches can help extend the limits of current adaptation strategies. Enhancing access to natural and financial capital can significantly improve adaptive capacity (Turner *et al*., 2022). Land tenure security, for example, increases worker agency through expanded investment options, better credit access, and reduced market dependence (Castro and Kuntz, 2022). Social protection programmes can further support autonomous adaptations (Garg, Jagnani and Taraz, 2020), while access to shaded work areas reduces direct heat exposure (Masuda *et al*., 2019).

Mechanization of outdoor work in agriculture and construction sectors shows promise for improving heat-induced productivity losses (Orlov *et al*., 2020). Technological solutions like improved cooling stations, moisture-wicking clothing, and early warning systems for extreme heat events can further enhance adaptation capacity.

Formal adaptation strategies implemented by governments and organizations must align with local everyday adaptation practices to be effective. Lindegaard and Sen (2022) note that formal interventions can sometimes disrupt local adaptation strategies by contradicting cultural preferences or livelihood routines. Successful adaptation requires supporting rather than replacing autonomous adaptations that communities have already developed.

MOSAIC LANDSCAPE SOLUTIONS FOR HEAT ADAPTATION: PATCH SIZE, TREE COVER AND WORKER HEALTH

Strategic land-use planning offers a powerful policy lever for reducing heat exposure among rural workers by guiding agricultural development towards configurations that could buffer temperature extremes and sustain ecosystem services. As a potential system-level adaptation strategy, land-use policy complements workplace practices, technological solutions and public health interventions. Thoughtful landscape design – such as adjusting field size and layout relative to surrounding forests and tree cover – could directly lower heat exposure and stabilize agricultural productivity (see *Local forest and climate benefits for agriculture*, **Chapter 3**). Evidence from remote sensing and field studies across the tropics shows that deforestation significantly increases local land surface temperatures, with the greatest warming where forest clearing is extensive and contiguous (see this chapter's *Deforestation patch size influences local temperature* section). In contrast, smaller clearings embedded within tree-rich landscapes experience less warming, likely due to the cooling influence of adjacent forest cover and atmospheric mixing (**Chapters 3–5**). These cooling processes can reduce time spent above occupational heat thresholds (e.g. WBGT-based thresholds; see **Table 8**),

supporting physical work capacity and lowering heat-related illness risk. By designing landscapes for cooling – favouring smaller agricultural patches interlaced with tree belts, riparian buffers and forest remnants – planners and producers can help protect worker health, extend safe working hours, and ease crop water stress (**Chapter 4**), while complementing other adaptation measures such as shade structures, work–rest cycles, hydration, and heat-aware scheduling.

Practical planning principles should translate the insights presented in this report into action, while acknowledging that further local and context-specific research is needed (see knowledge gaps in **Table 10**). To support implementation, the following strategies are inferred from the research summarized above. First, limit maximum patch sizes of deforested areas to prevent large, contiguous openings; where expansion is necessary within existing agricultural areas, stagger smaller clearings across space and time to preserve regional evapotranspiration and avoid synchronized peaks in heating. Second, maintain high edge-to-area ratios by interlacing fields with riparian buffers, shelterbelts and live fences at intervals that sustain their cooling influence across the production area. Third, place labour-intensive operations and worker resting points within or adjacent to shaded strips, agroforestry and community forests to reduce direct sun exposure during peak heat and preserve safe work windows. Fourth, align tree placement with water-smart design to jointly lower surface temperatures and improve soil water status.

Policy and governance tools can mainstream cooling-positive landscape designs. Zoning and permitting can include limits on maximum size of continuously deforested patches of land and minimum tree-retention or tree-cover ratios for new or reconfigured agricultural blocks. Incentives – payments for ecosystem services (PES), tax credits or preferential credit and insurance – can reward farms that demonstrate compliance with patch-size and tree-matrix criteria or measurable reductions in local maximum temperatures or land surface temperatures. Tenure security for communities and smallholders enables mosaic management and collective maintenance of shelterbelts and riparian buffers. Restoration initiatives and seed networks can supply native species for belts and buffers, aligning climate adaptation with biodiversity and water goals.

Finally, planning for smaller, cooler patches should not become a pretext for expanding agriculture into remaining natural forests. Mosaic layouts should be achieved through redesign, restoration and optimization within existing agricultural frontiers – not by creating new mosaics through conversion of intact forests or other natural ecosystems. In short, smaller agricultural patches can be cooler, safer and more productive, but these gains should not come at the expense of additional deforestation.

KNOWLEDGE GAPS

Despite growing evidence on the role of forests in mitigating heat exposure and supporting rural worker resilience, several critical gaps remain.

Table 10. *Knowledge gaps on the role of forests in mitigating heat exposure and supporting rural worker resilience*

KNOWLEDGE GAP	WHY IT MATTERS	PRIORITY ACTIONS
Regional and context-specific heat stress metrics	Misaligned heat thresholds may underestimate risks for acclimatized tropical populations, exposing rural workers to unsafe conditions or ineffective policies. Without accurate metrics, millions face heightened risk of heat-related illness and death.	Conduct field-based validation of wet bulb globe temperature (WBGT) and other heat exposure metrics in tropical agricultural settings; integrate local climate and work (e.g. intensity, timing) data.
Long-term health outcomes from chronic heat exposure	A better understanding of links to kidney disease and cardiovascular impacts could inform strategies to prevent these outcomes. Without reliable data, health systems cannot effectively prevent disability or death in rural populations.	Longitudinal studies on chronic heat exposure among rural workers; expand epidemiological datasets in tropical regions.
Economic consequences of heat-related productivity losses	Ignoring productivity losses underestimates economic risks. Heat stress could reduce gross domestic product gross domestic product (GDP), disrupt food supply chains, and deepen poverty in low-income tropical economies.	Develop integrated models linking heat exposure, crop calendars and economic output; quantify national and global costs.
Adaptation effectiveness and limits	Overestimating adaptation capacity creates a false sense of security. Without clear thresholds, behavioural and technological adaptations may fail under combined warming and deforestation, exposing workers to major health and livelihood risks.	Model physiological limits under future warming scenarios; document and evaluate adaptation strategies across diverse tropical contexts.
Gender and social equity dimensions	Women and marginalized groups face higher vulnerability due to tenure insecurity and cultural norms. Equity gaps undermine adaptation success and resilience.	Research gender-differentiated adaptation strategies; assess policy interventions for equitable pathways to resilience.
Landscape design for cooling services	Mosaic landscapes are important for providing cooling services, but empirical data on optimal patch size and tree configuration are limited. Evidence-based design tailored to local conditions is essential for maximizing adaptation and productivity gains.	Field experiments and remote sensing to quantify cooling thresholds; develop spatial planning guidelines for mosaic landscapes that maintain forests and sufficient tree cover.
Interactions between global warming and local land-use change	Few models assess how local and global warming jointly affect health and productivity, yet such integrated approaches are vital to anticipate compound risks to health, labor, and food security under climate change.	Build coupled climate–land-use–health models at fine spatial scales; scenario analysis for policy planning.
Monitoring and early warning systems	Rural workers often lack real-time heat alerts, leaving them vulnerable during extreme events. Early warning systems can reduce illness, death, and economic losses.	Develop low-cost, mobile-enabled heat-risk monitoring tools; integrate with local health and labour systems.

CONCLUSIONS

Forests are fundamental to agricultural resilience in the tropics as natural cooling systems that protect crops and rural workers. When forests are cleared, local land surface temperatures rise by 3–5 °C, creating hotter microclimates that amplify heat exposure (Vargas Zeppetello *et al.*, 2020). Between 2001 and 2020, this warming contributed to an estimated 28 330 additional heat-related deaths annually, with Southeast Asia bearing the greatest burden (Reddington *et al.*, 2025).

Impacts on livelihoods are equally stark. Field experiments in Indonesia show that workers in deforested areas experienced 8.2 percent lower productivity, spent more time above heat strain thresholds, and scored significantly lower on cognitive and episodic memory tests compared to those in forested settings (Masuda *et al.*, 2020, 2021; Suter *et al.*, 2019). At regional scales, deforestation increased unsafe work time by 0.31 hours per day, compared to just 0.03 hours in areas that maintained forest cover (Wolff *et al.*, 2020) . Projections indicate that with +2 °C additional global warming relative to the early twenty-first century, workers in deforested landscapes could lose up to 5 hours of safe work time daily, threatening food security and rural incomes (Parsons *et al.*, 2021).

Patch size matters: smaller agricultural clearings embedded within forested landscapes experience substantially less warming than large, contiguous clearings (Lawrence *et al.*, 2022). Remote sensing studies indicate that restoring trees in areas previously deforested for agriculture can provide significant cooling benefits – ranging from -0.32 °C to -2.4 °C per 10 tonnes of woody carbon per hectare (Vargas Zeppetello *et al.*, 2022). These findings underscore the role of landscape design: maintaining forest fragments, riparian buffers and tree belts can help reduce heat exposure for workers and crops while supporting broader ecosystem services.

Protecting and restoring forests is therefore not only an environmental imperative but a cornerstone of agricultural adaptation. Forests and tree-based systems – such as agroforestry and silvopasture – offer measurable cooling services that preserve safe working hours, stabilize yields and safeguard rural health. In a warming world, forest conservation is essential for sustaining agriculture and the well-being of the more than 1 billion tropical outdoor workers facing intensifying heat stress (Masuda *et al.*, 2024).

BOX 12

From local knowledge to regional impact: building the causal chain linking deforestation, heat and human health – A case study from Berau regency, East Kalimantan, Indonesia

Recognition by villagers of the health benefits of forest cooling inspired further research

In 2008 and 2009, The Nature Conservancy conducted a survey of over 4 600 people from nearly 500 villages in Kalimantan to better understand how rural communities interacted with orangutans. Fortunately, the survey included an open-ended question about whether forests were important for health, and why. The most common response – shared by 28 percent of the 4 634 respondents – highlighted forests as essential for keeping local temperatures cool (Wolff *et al*., 2018). Villagers provided statements such as, "the forest gives protection from heat, which is very important for our health," and "since the decline in forest areas, the weather is hotter." This finding prompted The Nature Conservancy to delve deeper into the data to explore why villagers perceived forests to play a role in temperature regulation. This raised concerns that people were noticing the cooling effect of forests because they were increasingly exposed to rising heat caused by deforestation.

Researchers confirmed that these perceptions aligned with measurable environmental conditions. Villager perceptions about the importance of forest cooling services proved particularly strong in villages with higher or more variable temperatures and in recently deforested or fragmented landscapes. The research highlighted forests' vital role in regulating local climate – an ecosystem service increasingly threatened yet essential for mitigating heat-related illness and adapting to climate change (Wolff *et al.*, 2018).

A comprehensive field experiment

The clear signal from village surveys prompted a series of carefully designed field experiments to quantify the relationship between deforestation, heat exposure, and human health outcomes. These experiments, conducted in Berau regency, East Kalimantan, aimed to move beyond anecdotal evidence to establish causal links between forest loss and specific physiological, cognitive and productivity impacts. Researchers recruited 363 healthy adult participants from ten villages to participate in a randomized study, where they conducted 90-minute outdoor activities representative of typical work in either forested or deforested settings.

Environmental measurements confirmed substantial temperature differences between the settings. Ambient near-surface air temperatures measured in the shade were 2.1 °C higher in deforested areas, with black globe temperatures (Tb) (which account for radiant heat) 10 °C higher (Masuda *et al*., 2020). Wet bulb globe temperatures (WBGT), which incorporate humidity and radiant heat and are critical for assessing heat stress, were on average 2.8 °C higher in deforested settings (Masuda *et al*., 2021).

Physiological heat strain

One key finding from the field experiment concerned direct physiological impacts. By monitoring participants' heart rates and using validated algorithms to estimate core body temperature (CBT), researchers identified significant differences between forest and non-forest settings. The study of

Continued on next page

363 participants showed that those in deforested conditions (n = 159) spent an average of 3.1 additional minutes, over the 90-minute activity, with CBT exceeding 38.5 °C compared to those in forested environments (n = 172), even after adjusting for variables like age, sex, and body mass index (Suter *et al.*, 2019).

This effect was particularly pronounced during afternoon hours when ambient temperatures peaked – participants who began the experiment after noon experienced 5.2 additional minutes above the critical temperature threshold. These extended periods with elevated CBT represent a meaningful physiological strain that can contribute to heat-related illnesses and other adverse health outcomes, demonstrating that forest cover provides tangible protection against dangerous heat exposure (Suter *et al.*, 2019).

Cognitive performance

The same experimental design revealed significant impacts on cognitive function. After completing their assigned tasks, participants took standardized cognitive assessments measuring general cognitive ability and memory function. The results showed that participants in deforested settings had statistically significant lower scores on both cognitive assessment tests and episodic memory tests compared to those in forested settings (Masuda *et al*., 2020).

These impacts were not uniform across all participants – male participants and those working during peak afternoon heat showed the most pronounced cognitive effects. This finding indicates that heat exposure from deforestation impairs mental functioning, potentially affecting decision-making, learning, and other cognitive processes essential for well-being and livelihood activities (Masuda *et al*., 2020).

Labour productivity

The experiment also quantified economic impacts through measurements of work productivity. Researchers documented that those participants working in deforested settings showed 8 percent lower productivity compared to those in forested environments (Masuda *et al*., 2021).

Analysis of work patterns revealed that this productivity decline stemmed primarily from behavioural adaptations – specifically, workers taking more frequent breaks when exposed to higher temperatures. This finding suggests that people instinctively modify their work behaviour to protect themselves from heat stress, but at a cost to their economic output. By moderating local temperatures, forests allow for more continuous productive work (Masuda *et al*., 2021).

Current adaptation practices

To understand how rural communities are already responding to increased heat exposure, researchers conducted surveys in the same villages where the experiment was conducted. The surveys identified how workers adapt to hotter conditions by adjusting work schedules and taking strategic breaks. Different adaptation strategies emerged between those who work exclusively in open areas versus those who work in both forested and open settings, suggesting that regular access to forest cooling influences how people manage heat exposure. Alarmingly, workers in fully deforested areas faced up to 6.5 hours of exposure to WBGT exceeding recommended safety thresholds under a heavy workload (Masuda *et al*., 2019).

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Scaling up: remote sensing assessment of regional health impacts

The consistent findings from these experimental studies motivated researchers to scale up their analysis to assess regional impacts using remote sensing and climate model projections. This approach allowed them to quantify the effects of historical deforestation and project future impacts under various levels of future global warming.

Using data at 1 km^2 resolution, researchers compared forest cover and temperature conditions in Berau regency, Indonesia, between 2002 and 2018. During this period, approximately 4 375 km^2 of forested land (17 percent of the entire regency) was cleared. This deforestation increased mean daily maximum temperatures by 0.95 °C and mean population-weighted daily temperatures by 0.86 °C (Wolff *et al*., 2020). This warming was associated with a modelled 7.3–8.5 percent increase in all-cause mortality, translating to a modelled 101–118 additional deaths annually by 2018. Furthermore, unsafe work time increased over the 2002–2018 period by 0.31 hours per day in deforested areas compared to just 0.03 hours per day in areas that maintained forest cover (Wolff *et al*., 2020).

Projecting future impacts of global climate change

Researchers estimated future impacts of heat in deforested areas by modelling the combined effects of historical deforestation and future global climate change. With 2 °C of additional global warming relative to 2018 levels, recently deforested areas could face a 17–20 percent increase in all-cause mortality (236–282 additional deaths per year) and up to 5 hours of unsafe work conditions per day (Wolff *et al*., 2020). These projections underscore that heat exposure from combined deforestation and climate change already affects populations in tropical regions, with impacts intensifying with additional global warming.

Implications for policy and practice

The progression from village perceptions to experimental evidence to regional modelling provides a comprehensive understanding of the role of forests in regulating local temperatures and protecting human health. As Masuda *et al.* (2020) concluded, "policymakers should consider how land-use planning that takes into account the cooling services of trees can play a significant role in increasing resilience to heat from climate and land-use change in the tropics."

The research collectively demonstrates that forests provide a crucial but often overlooked ecosystem service – natural air conditioning that protects rural communities from heat exposure. This service becomes increasingly valuable as global temperatures rise due to climate change. Land-use decisions should consider both local health impacts of deforestation and forests' broader climate mitigation benefits.

The findings point to the need for adaptation and mitigation policies specifically designed for rural working populations and that build upon existing coping strategies. By recognizing the cooling value of forests and incorporating this knowledge into planning, policymakers can help protect the health and economic resilience of vulnerable rural populations in the tropics.

As tropical regions face the dual challenges of development pressures and climate change, preserving forest cover emerges as not just an environmental priority but a potential critical public health intervention with immediate local benefits. The cooling services from forests, as Masuda *et al.* (2021) concluded, "have the potential for increasing resilience and adaptive capacity to local warming," a benefit that deserves greater recognition in policy decisions affecting tropical landscapes.

Sources: See full box references at the end of the bibliography section.

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CHAPTER 6

Contribution of biodiversity-mediated and other forest ecosystem services to agriculture

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KEY MESSAGES

- **Forests and trees can enhance agricultural productivity: Forests and trees deliver vital ecosystem services – such as pollination, biological pest control, nutrient cycling, erosion control, fodder, mulch, and climate regulation – that enhance crop yields and sustain ecosystem health.**
- **Integrated landscapes strengthen climate resilience and food security: Incorporating trees and forest patches into agricultural systems can reduce dependence on synthetic inputs, enhance resilience to climate variability, and support the production of diverse, nutrient-dense foods.**
- **Proximity to forests offers benefits and trade-offs: Fields near forests may benefit from stronger ecosystem services, especially pollination and biocontrol, but may also experience disservices such as increased exposure to certain pests.**
- **Policy must support multifunctional landscapes: Existing policy frameworks tend to address ecosystem services in isolation and could be better tailored to support integrated production systems that balance food production with the conservation of trees and forests, and biodiversity.**

INTRODUCTION

Forests and trees are prominent on the global agenda, largely due to their contribution to climate change mitigation and adaptation and biodiversity conservation. Building on previous chapters that cover the regional and subregional climate and hydrological benefits of forests and trees for agriculture, this chapter reviews a broader range of farm-scale ecosystem services. These include the less explored and understood biodiversity functions of forests and trees that support agriculture (e.g. pollination and biocontrol), how forests and trees influence soil functions underpinning

agriculture and other ecosystem services, including microclimate regulation and the provision of forage, fodder, mulch and fuelwood.

Forests and trees contribute to food production in a myriad of ways through the provision of ecosystem services. The direct provisioning services provided by forests (i.e. non-wood forest products including fruits, seeds and nuts) are known to significantly contribute to rural household food security and income, and act as a safety net in times of food shortages (Ickowitz *et al.*, 2022; Ndoli *et al.*, 2021). However, the indirect contribution of forest ecosystem services to agriculture is less well established, despite an evolving but fragmented body of research. These indirect ecosystem services include regulating services such as soil quality, pollination and pest control, supporting services such as nutrient cycling, soil formation and habitat for wildlife, as well as some provisioning services, including the provision of fodder for livestock production and fuel for cooking. In this chapter, we summarize some of the findings in the scientific literature on the indirect contributions of forest ecosystem services to agriculture and synthesize advances in the recent research. We illustrate the contributions of multiple ecosystem services provided by forests and trees to agriculture by highlighting three case studies focusing on pollination and biocontrol, biomass yields and the linkages between soil quality and nutrition.

The evidence presented in this chapter focuses on primary forests and native tree species, emphasizing their ecological, biophysical and socioeconomic significance. It excludes the establishment of non-indigenous trees and planted forests, which can also contribute to agricultural sustainability objectives but whose mechanisms, structures and functions differ from native trees and forest ecosystems.

The chapter first presents biodiversity-mediated forest benefits for agriculture, which include ecosystem services related to pollination and biocontrol. We classify these processes as biodiversity-mediated, because they are enabled or enhanced by the presence and functions of biological species more diverse than they would be without the presence of forests and trees in the location or vicinity.

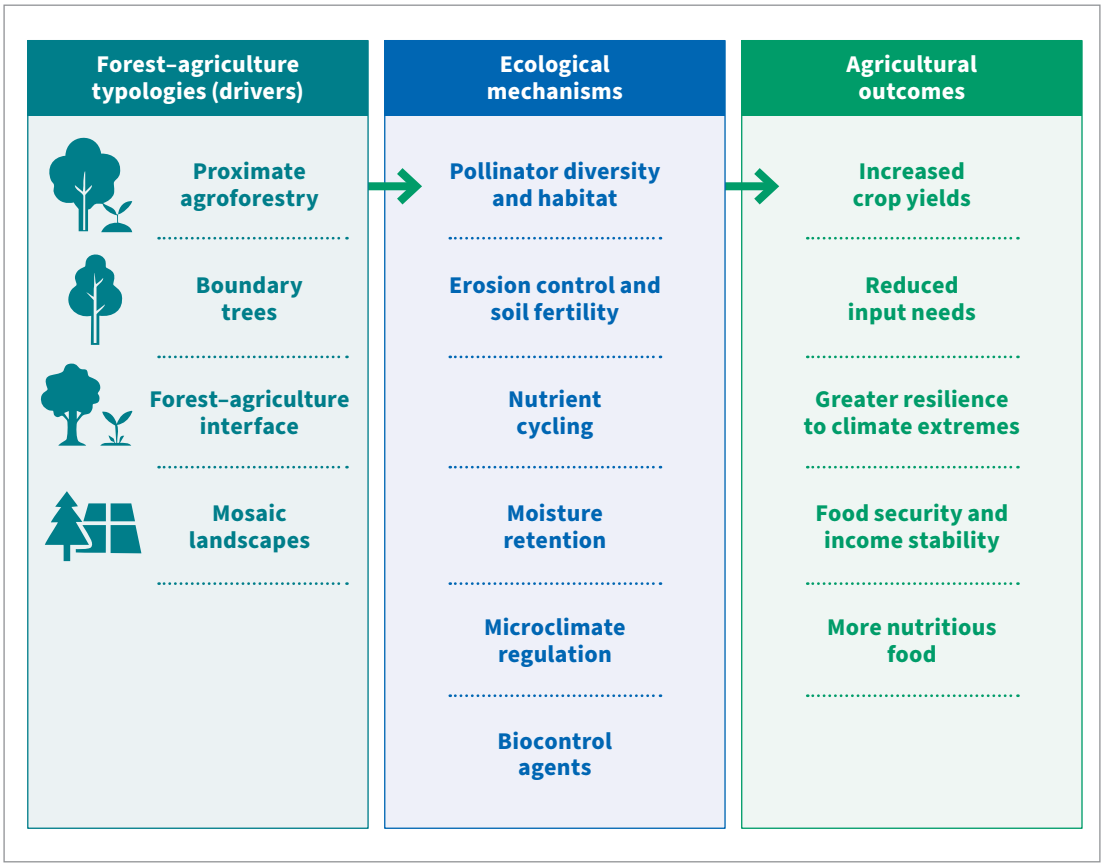
Then, the chapter presents soil-related functions and their contributions to agriculture. While hydrology-related soil functions are already described in **Chapter 4**, here these are presented in a more comprehensive manner, together with nutrient cycling processes and effects of increased soil biodiversity. Finally, other ecosystem services including microclimate regulation and the provision of forage, fodder, mulch and fuelwood are also described and discussed.

The direct primary productivity of forests and trees, and their indirect supply of regulating and provisioning ecosystem services can be considered the main determinants of forest benefits for agriculture (**Table 11**). Variations in forest–agriculture systems, which are classified

Table 11. *Summary classification of ecosystem services*

CATEGORY	DIRECT ECOSYSTEM SERVICES	INDIRECT ECOSYSTEM SERVICES
Provisioning services	Fruits, nuts, seeds, fibres (NWFPs), mulch, forage and fodder for livestock, fuelwood for cooking, edible plants, resins, latex, and other plant extracts	Plant regeneration and natural propagation, genetic diversity of wild relatives
Regulating services	Microclimate (shade and cooling effects)	Pollination, pest control, soil stabilization and erosion control, moisture retention
Supporting services	*(Generally indirect)*	Nutrient cycling, soil formation, habitat for beneficial species, seed dispersal
Cultural services	Food-related traditions, recreation, including ecotourism and hiking	Landscape aesthetics, identity, cultural cohesion

Figure 9. *Summary illustration of major forest–agriculture system typologies, ecological mechanisms and agricultural outcomes of biodiversity-mediated forest benefits for agriculture*



by how the landscape is organized, regulate the benefits they provide. Adjacent forests, mosaic landscapes and trees on farms provide slightly different or similar benefits at varying intensities. Underpinning these typologies of forest–agriculture systems are various ecological or human-related mechanisms that spatially link forests and trees to agricultural landscapes and crop and animal productivity, ultimately providing human benefits (**Figure 9**). These mechanisms – including floral abundance and diversity, habitat suitability (for insect and bird nesting and feeding), nutrient cycling, erosion control, moisture retention, shading and temperature regulation, and as sites of microorganism concentration – provide a conduit for onward productivity benefits. In an era of intensifying global change, understanding these mechanisms and the intricate interactions that stimulate benefits is more crucial than ever to better safeguard, and where appropriate, manage the biodiversity, soil and other functions of forests and trees that support agriculture.

The following sections aim to provide a synthesis of current knowledge on the drivers and mechanisms of forests and trees in supplying benefits for agriculture, with particular focus on the ecosystem services of pollination, biological control of pests, soil functioning (including nutrient cycling and erosion control), and several other ecosystem services (microclimate regulation and provision of forage, fodder and mulch biomass). In addition to elaborating the benefits of these ecosystem services, and the processes that shape their availability and flow to agriculture, ecosystem disservices are also considered. At a larger spatial scale, global change drivers such as land-use intensification and climate change are also covered in brief, including the threats these pose to forest benefits for agriculture.

BIODIVERSITY-MEDIATED FOREST BENEFITS TO AGRICULTURE

This section highlights the pollination and biological control benefits facilitated by forests and trees, and their role in supporting sustainable crop production.

Facilitating pollination services

As a key regulating service, pollination is one of the most well studied of the indirect ecosystem services provided by forests and trees (Reed *et al*., 2017). This is likely due to pollinators being above ground and visible, and therefore relatively easily researchable. Forests and trees provide habitat and resources (e.g. tree resin, floral and non-floral resources) for wild pollinators such as bees, butterflies, birds and bats, which are estimated to contribute to the productivity of more than 75 percent of all crops (Potts *et al*., 2016). These pollinators are vital for some of the world's most traded food products such as coffee and cocoa (Potts *et al.*, 2016). Indeed, more than 50 percent of internationally traded crops depend on pollinators (Marques *et al*., 2024). Recent research has revealed that pollinator-dependent agriculture is increasing globally, and more rapidly in the tropics, yet agricultural diversity, which would enhance pollinator supply and efficiency, is decreasing (Aizen *et al*., 2019). Several studies, including those by Blanche, Ludwig and Cunningham (2006), Klein *et al.* (2007) and Severiano-Galeana *et al.* (2024) utilized a forest distance gradient to determine the impact and thresholds for pollinator success and effects on yields. However, a study by Boreux *et al.* (2013) observed an overall negative effect, attributed to richness of surrounding forests and abundance of floral resources, which limit pollinator activities in proximate agriculture systems. Another study indicated mixed results, finding that non-intensive

farming systems were suitable for pollination while forest proximity has no significant effect (Frimpong *et al*., 2011).

Forests, by virtue of their structural and compositional complexity, including diverse tree species, understory vegetation and variety of microhabitats, can provide abundant nesting sites, floral resources and microclimates that sustain a variety of pollinators (Ulyshen *et al*., 2023). Such pollinator diversity facilitates functional complementarity and synergistic contributions to crop yield and quality (Garibaldi *et al*., 2013). Different pollinators are active at different times of day, have varying responses to weather conditions, and exhibit different microhabitat preferences, which means that a mix of species ensures greater resilience and stability of pollination under fluctuating environmental conditions (Garibaldi *et al*., 2013). In contrast, monogenous habitats that support fewer species can create vulnerability, as shown by declines in crop yields during colony collapse or disease outbreaks (Potts *et al*., 2016).

While it is hard to place an economic value on pollination, in 1997, it was estimated that the derived benefits could be in the region of USD 117 billion per year (Costanza *et al*., 2017). It can be assumed the value is now significantly higher, and a recent study estimated a range between USD 195 billion to approximately USD 387 billion annually (Porto *et al*., 2020). Research investigating the role of forests in facilitating pollinator–crop yield interactions has generated recent interest and renewed effort. This has led to an increasing acceptance of the critical role of forests in supporting global pollinator diversity (Alison *et al*., 2022; Maurer *et al*., 2022; Ulyshen *et al*., 2023) and their contribution, via pollinating services, to crop production in adjacent habitats (Reed *et al*., 2017).

There have been worrying declines in the numbers of pollinators (Sánchez-Bayo and Wyckhuys, 2019), yet consumption of pollinator-dependent crops is increasing, as is deforestation, particularly in the tropics. While forest loss is not the only factor driving pollinator decline, this confluence of interrelated factors is a serious concern for future food security globally and especially within the global south (Potts *et al*., 2016; Turo *et al*., 2024). Pollinator decline threatens food security by reducing the yields of essential food crops, such as vegetables, thereby limiting household food stocks. At the same time, it lowers the productivity of globally traded industrial and export crops, leading to income losses for farming households and reducing their ability to purchase nutritious food. Together, these effects contribute to deficits in both caloric intake and essential nutrients. Moreover, although the evidence for the direct effect on pollinators is incomplete, the impacts of climate change are likely to further exacerbate these dynamics. In addition to the unsustainable use of agrochemicals, which accelerate decline and disrupt the distribution of pollinators, forest loss and the degradation of natural habitats are also considered to be among the primary drivers of pollinator decline (Ollerton *et al*., 2014; Sánchez-Bayo and Wyckhuys, 2019). Meanwhile, the potential for forests to mitigate the impacts of climate change will likely enhance their importance for pollinators and therefore future food security (Ulyshen *et al*., 2023). Forest loss is primarily driven by intensive agricultural practices that have led to the increased abundance of monocultures, which negatively impact pollinators due to reduced food sources and the distance between available patches becoming greater. Such intensification is also associated with the removal and destruction of hedgerows and field margins, which reduce the number of viable nesting sites for many pollinator species. For example, in the United Kingdom of Great Britain and Northern Ireland, since the 1930s, more than 30 percent of hedgerows have been lost as agriculture has become increasingly intensive (Osborne, Williams and Corbet, 1991), while in Germany, the removal of similar habitats has been strongly associated with dramatic declines in bee fauna (Westrich, 1989).

Habitat for wild pollinators surrounding crop fields has been researched on a regional (Sitotaw

et al., 2022), continental (Koh *et al*., 2016) and global scale (Dainese *et al*., 2019). However, our understanding of pollinating services is far from complete, with several key gaps previously identified, and in particular the role of forests and trees within the pollinator–crop yield dynamic. This is largely due to the evidence base being dominated by studies that are short term and focus on the effect of either habitat loss (i.e. how pollinators respond to land-use change) or distance to forest on pollination (assessing forest gradient effect on pollinator foraging ranges). Furthermore, the majority of studies tend to be conducted at the farm or patch rather than landscape level. Finally, there has been a disparity in research efforts between temperate and tropical regions, with the former receiving significantly more attention; likely due to the pollinator crisis, and particularly strong bee declines in the global north, that received widespread attention at the end of the last century (Viana *et al*., 2012). Therefore, significant gaps remain related to how landscape structure impacts pollinator behaviour and efficiency, and whether patterns hold across landscapes and biomes. For most food crops, the identity and efficiency of pollinators across key growing regions also remain poorly understood (Arachchige *et al*., 2023).

Based on our current understanding, "any effort to preserve native woody habitats, including the protection of individual trees, will benefit pollinating insects and help maintain the critical services they provide" (Ulyshen *et al*., 2023).

Facilitating biological control

Biological control involves the use of living organisms to control infectious pestilential organisms (Stenberg *et al*., 2021), including but not limited to crop weeds, microbial pathogens and pest insects. In ecological terms, biological control (or "biocontrol") can show many parallels with pollination in terms of how forests and tree cover can modulate the flow and provision of this ecosystem service to agriculture (Hohlenwerger *et al*., 2024; Medeiros *et al*., 2022). This is especially apparent for parasitoid wasps and other predatory insect biocontrol agents, which tend to show considerable overlap with pollinators in terms of habitat nesting, foraging needs and behaviours. As such, many of the drivers, mechanisms and impacts elaborated above for pollinators may also apply in tandem for insect biocontrol agents although forests, trees and hedgerows affect vertebrate biocontrol organisms, such as birds (Boesing, Nichols and Metzger, 2017), differently. In less common cases, some organisms that positively associate with forests or forest margins have the ability to provide both pollination and biocontrol services to crops (Dunn *et al*., 2020; Tooker, Hauser and Hanks, 2006). This is the case of certain tachinid flies and aphidophagous hoverflies, which as larvae, parasitize or prey on agriculturally important pests, and as adults are frequent or obligate flower feeders and potential pollinators.

Landscapes dominated by forests or agroforestry often support thriving populations of wild biocontrol agents, with positive spillover effects on crops from these natural or semi-natural habitats or patches (González, Salvo and Valladares, 2015). In addition, the biocontrol of crop pests can also have positive impacts on forests by reducing land-use pressure, and in particular deforestation. A notable case has been the introduction of a host-specific parasitoid of mealybug in Southeast Asia, which led to increased cassava yields and a subsequent reduction in clearance of tropical forest for agricultural production (Wyckhuys *et al*., 2019).

Similar to the case of pollinators, there exists an extensive literature base demonstrating a generally positive relationship between the composition and diversity of non-crop habitat surrounding and within agricultural fields and landscapes, and the abundance and diversity of biocontrol agents active within crops (Bianchi, Booij and Tscharntke, 2006). However, there are also instances where no such relationships exist, as in one study of Argentinian agricultural landscapes that demonstrated no spillover of

BOX 13

Forest benefits for pollination and sustainable pest and weed control in Karnali province, Nepal

Karnali province is one of seven federal provinces of Nepal and has a population of over 1.5 million. It is one of the most remote and mountainous areas of the country, with an estimated 28.9 percent of people living in absolute poverty, and 51.2 percent multidimensionally poor (Karnali Province Planning Commission, 2020). With a vision to support and develop agricultural livelihoods, the Government of Karnali province in 2018 committed to transitioning all farming and forest production in the province to organic production systems. For this purpose, FAO Nepal was mandated to provide technical capacity support under the project "Strengthening capacity of public and private sector stakeholders for promotion of organic agriculture in Karnali province of Nepal". The project defined key policies and practical guidelines to support organic farming for four crops (apple, orange, ginger and turmeric) and over its course from 2020 to 2023 conducted growing trials and held Farmer Field Schools (FFS) across four districts.

Among the guidelines developed and disseminated in FFS were practical techniques for farmers to exploit synergies between agroecosystem services (including soil decomposition and nutrient cycling, biological pest control, and pollination). Habitat quality of surrounding forest cover was deemed to be particularly critical in apple and orange agroecosystems to provide good forage and nesting resources for beneficial insects. Fruit yields and quality were noticeably high with increased pollinator and biocontrol benefits. Similar results were reported in Mexico by Severiano-Galeana *et al.* (2024), who observed increased fruit quality and yields for plants close to forest patches since they received more frequent visits from pollinators.

Via the FFS, farmers were encouraged to protect such forest areas and their margins rich in flowering herbs, which in addition provided sources of the home-made biopesticide jholmol (e.g. stinging nettle), and plants that simultaneously provided both excellent forage for pollinators and biocontrol agents and biopesticidal compounds (e.g. the Chinese chaste tree *Vitex negundo*). Another area in which forests provided critical agroecological services was through their provision of mulch material for weed control. Here, agreements were established between farmers and local forest user groups to collect pine needles for application as mulch in ginger production, which from the growing trials was seen to lead to higher yields of ginger rhizomes.

Sources: See full box references at the end of the bibliography section.

biocontrol services by invertebrate and vertebrate predators from fragments of original chaco serrano forest (Ferrante, González and Lövei, 2017). Also, as with pollination services, the magnitude of the benefits of forest, semi-natural or hedgerow habitat for biocontrol services to crops depends on the intensity of agricultural production in a landscape in which intensively farmed landscapes are likely to benefit most from the presence of non-crop habitat such as tree and forest patches (Bartual *et al.*, 2019).

Much of the evidence base demonstrating the benefits of forests for crop biocontrol services comes from the study of temperate agricultural production systems, and knowledge of tropical and subtropical forests and cropping systems is sparse in comparison (Medeiros *et al.*, 2019). However, an exception to this trend is agroforestry systems for

perennial crops such as coffee, cocoa and plantain where decreased prevalence of both parasitic and non-parasitic weeds, along with increased populations of natural enemies have been noticed (Pumariño *et al*., 2015). In Brazilian plantations, for instance, it has been shown that outbreaks of the coffee leaf miner *Leucoptera coffeella* (Lepidoptera) were effectively controlled by native social wasps (Vespidae, Polistinae), whose richness, diversity and biocontrol services positively increased with increasing forest cover, from local to landscape scales (Medeiros *et al*., 2019). In contrast, such effects were less evident in annual crops such as maize, rice and beans (Pumariño *et al*., 2015).

The density of forest edges and transitional zones between forests and surrounding crops or other habitats may often underpin the benefits rendered by forests as crop biocontrol services (Hohlenwerger *et al*., 2024). The microclimate composition and structural diversity of vegetation in such areas tend to be different from forest interiors, which can better provide biocontrol agents, with forage, nesting and shelter sites that are elsewhere scarce or unavailable. It is well noted, however, that forest edges and transitional habitats in proximity to crop fields can also harbour crop pests, such as by providing overwintering sites and refugia from which crop infestations may sporadically or repeatedly occur. Managing this forest ecosystem disservice to crops is therefore a key question to grapple with. Such disservices are more likely to materialize in intensive agricultural landscapes that otherwise show reduced diversity or cover of semi-natural habitat (Bartual *et al*., 2019). And so, one potential solution can be to increase forest and semi-natural habitat cover, to better ensure trophic complexity and resultant biocontrol pressure on potential pests also in these forest edge areas.

THE ROLE OF FORESTS AND TREES IN SUSTAINING SOIL FUNCTIONS

Existing scientific evidence demonstrates that trees have a profound effect on multiple soil functions. Trees contribute to soil health in various ways that can be broadly categorized as processes that increase inputs to the soil, reduce losses from the soil, and enhance the physical and chemical condition of the soil.

Soil amendment

Some tree types enrich soils and support the growth of surrounding crops, reducing farmers' production costs. Such "fertilizer trees" are often nitrogen-fixing and are incorporated in different farming systems, such as through fallowing in shifting cultivation and tree–crop intercropping (Rosenstock *et al*., 2014). While much of the nitrogen fixed by such trees is used by the tree itself for its own growth, there is good evidence of the contributions of leguminous trees to improving soil fertility (see Kaba *et al*. [2019] and Nygren *et al*. [2012]). Moreover, the litter from these trees is nitrogen-rich, thereby further contributing to soil fertility via decomposition. Variations in soil organic matter content are affected by the tree species, quantity of litter, rate of atmospheric nitrogen fixation and tree root formation and decomposition rates (Haghverdi and Kooch, 2020; Kamau *et al*., 2020). Certain tree species, especially broadleaved ones (Kooch, Samadzadeh and Hosseini, 2017), are better than others at improving soil fertility in the canopy area (Kamau *et al*., 2020). Trees such as acacia, alder and birch are known for nitrogen fixation (Mäkipää *et al*., 2018; Salmon *et al*., 2019) while eucalyptus and jackpine release substances that increase soil phosphorus levels (Cui *et al*., 2023).

Nutrient cycling

High rainfall intensity, soil porosity and the absence of vegetative cover can increase soil water percolation and associated leaching of nutrients into deeper layers of the soil below the rooting zone, making them unavailable for crop production (Tully, Lawrence and Scanlon, 2012; Zhang *et al*., 2023). Through deep root structures, trees can reverse leaching by extracting nutrients from deep soil layers, storing them in biomass and making them bioavailable for crops in the topsoil layer through the process of litter decomposition (Isaac and Borden, 2019; Pardon *et al*., 2017). This nutrient cycling service naturally improves soil quality as it forms a key part of humus (rich organic soil layer) formation, which increases proportionally to tree density and litterfall quantity and quality (Haghverdi and Kooch, 2020; Muchane *et al*., 2020). Trees further mitigate nutrient loss by utilizing and recycling excess nitrogen from conventional agriculture systems that involve intensive soil amendments. They act as nutrient pumps with rising nutrient utility as tree numbers and biomass yields increase on farms (Tully, Lawrence and Scanlon, 2012).

Nutrient mobilization

Soil mycorrhizal fungi are known to form symbiotic relations with plant roots in which nutrients are exuded to the fungus to stimulate reproduction and function, while the plants receive nutrient mobilization services and protection from pathogens (Bais, Broeckling and Vivanco, 2008; Sardans *et al*., 2023). By virtue of their perennial nature, trees on farms can promote beneficial mycorrhizal fungi populations, especially in conventional agriculture systems where soil disturbance and seasonal cropping disrupt soil functions. Though largely concentrated under tree canopies, mycorrhizal fungi play a key role in plant growth, nutrient assimilation and yield increment by mobilizing nutrients and making them available for plants (Dierks *et al*., 2021; Li *et al*., 2021; Sardans *et al*., 2023). However, they can also disarm some plant defences and foster the activities of parasitic nematodes (Frew *et al*., 2018).

Soil structure and erosion control

Tree roots improve soil structure by enhancing aggregate formation and stability, and increasing soil resistance to disruptive forces. By holding together surrounding soil, roots provide reinforcement to crops (Lucas *et al*., 2019), supporting the core soil function of anchoring plant roots, which reduces crop losses during severe weather events. By creating a conducive environment for soil microorganisms, trees support bioturbation, which involves biological alteration of the soil structure through creating intricate subterranean structures. This process is partly driven by activities of ecosystem engineers, such as termites, earthworms, ants and rodents, which facilitate the mixing of soil constituents and engage in upward and downward conveyance of soil sediments and organic matter (Meysman, Middelburg and Heip, 2006; Ruiz, Hallett and Or, 2023).

Tree presence and density on farms determine the intensity of soil erosion (Flores *et al*., 2020) by serving as windbreaks, slowing down the velocity of runoff water, and intercepting and converting rain into throughfall and stemflow. Farms with multilayered tree canopies that produce a thick litter layer or are interspersed with cover vegetation reduce soil displacement. Tree roots improve percolation of runoff water into the ground by creating biopores, while their binding effects enhance soil stability and resistance to erosion (Muchane *et al*., 2020). Recent estimates show that trees on farms can reduce soil erosion by 30 percent (Song *et al*., 2019) to 50 percent (Muchane *et al*., 2020), in comparison to monocultures.

Soil hydrology

Trees optimize soil health through their shading effects (both via canopy and litter), which moderates soil temperature, increases moisture retention, and supports the functions of microorganisms that are lost or rendered dormant during extreme heat exposure (Vandenbeldt and Williams, 1992). Some tree species (including longleaf pine) have the capacity to access deep groundwater sources and move the water upwards for use through hydraulic redistribution processes. They can release up to 50 percent of total water intake in shallow soils, helping maintain soil moisture and enhancing drought resistance for understory crops (Belovitch, Brantley and Aubrey, 2022; Kizito *et al*., 2012). Trees may also provide a disservice to agriculture by competing for nutrients, sunlight and water with cultivated crops, leading to lower productivity (Luedeling *et al*., 2016). For example, a study in Canada showed that tree shading effects linked to resource competition reduced yields in patches close to trees (within 2 m) despite high moisture and litterfall (Reynolds *et al*., 2007).

Forest edge effects

While much of the evidence around tree contributions to soils is limited to trees on farms, emerging evidence shows microclimate and soil chemical composition create conditions that increase the activities of forest edge decomposers, leading to higher rates of nutrient cycling (Remy *et al*., 2018; de Smedt *et al*., 2016). Other studies focus on soil microbial colonization in adjacent agricultural landscapes, illustrating how field impacts of forests are largely limited by biogeographical variations in the soil environment, typically salinity, temperature and pH. For instance, Dickie and Reich (2005) and King *et al*. (2022) show high microbial activity on adjacent soils 15–20 m from forest edges or trees on farms, with species richness declining relative to distance from forests or trees. Still emerging evidence shows how soils near forests have higher organic matter content and can contribute to increasing the availability of crop micronutrients vital for human nutrition (Wood, Tirfessa and Baudron, 2018).

BOX 14

Quality of forest-adjacent soils

Soil organic matter underlies crop nutritional quality and productivity in smallholder agriculture.

To feed growing populations, agriculture has shifted its focus to high-yield crops like wheat monocultures, which provide needed calories without attention to the range of nutrients needed for a balanced diet. Hence, despite high wheat yields in southeastern Ethiopia, many households face "hidden hunger", a severe deficiency in essential vitamins and minerals. Wood *et al.* (2018) investigate the relationship between soil organic matter in fields at varying distances from nearby forests and the nutrient content in wheat crops.

Fields with high proximity to forest where soils are naturally enriched by decaying plant material and animal manure showed higher soil organic matter concentrations relative to farther away fields, an indication that organic matter concentrations follow a distance-to-forest gradient. Wheat grown on forest-adjacent soils rich in organic matter was found to have high yields and greater concentrations of zinc and protein than wheat grown on farther away fields. For every 1 percent increase in soil organic matter, there was an increase in zinc enough to meet the daily needs of an additional 0.2 people per hectare, and enough protein for 0.1 more people. Although these increases are modest, they are crucial in the fight against hidden hunger by producing more nutrient-dense crops on soils naturally enriched by organic matter from adjacent forests, or tree litterfall on farms.

Source: Adapted from Wood, Tirfessa and Baudron (2018). For full box reference at the end of the bibliography section.

OTHER ECOSYSTEM SERVICES PROVIDED BY FORESTS TO AGRICULTURE

Trees both inside and outside forests provide many other ecosystem services, some of which have received less research attention than pollination, biocontrol and soil functions.

Microclimate regulation

Trees in agroforestry systems can favourably alter microclimates at the field scale by reducing temperatures and reducing evapotranspiration resulting in increased growth and yield of crops (Rosenstock *et al*., 2019). The role of forests and trees in water regulation is quite complex and multiscalar, with scientists suggesting that they can affect hydrology from a continental to a plot scale (Creed and Van Noordwijk, 2018; Ellison *et al*., 2017).

Forage and fodder

Livestock around the world feed on leaves from trees in forests and grasses from underbrush as part of their diets especially in tropical humid areas. There have been contentious debates on whether this practice degrades forests or enriches them (Mazzini, Relva and Malizia, 2018; Wisdom *et al*., 2006). Silvopastoral systems integrate trees with pasture to capitalize on the benefits that trees provide to livestock – these include the nutrients from their leaves but also shade and cooling services in hot climates. There has been extensive research into the different species of trees that can provide nutritious fodder to livestock. One study from sub-Saharan Africa, for example, found that leaves of leguminous fodder shrubs (calliandra) from agroforestry systems constitute a protein-rich supplement for livestock, increasing milk and meat production (Rosenstock *et al*., 2019). In Kenya, the increases in milk production attributable to nutritious fodder shrubs in agroforestry systems bring an estimated net income gain of USD 1.3–2 million per annum (Place *et al*., 2009).

Mulch

Tree litter functions as an eco-friendly protective ground cover – mulching material – which aids in weed suppression, moisture retention, temperature insulation and nutrient supply, and decreases splash erosion caused by raindrop impact, which displaces soil particles (Demo and Asefa Bogale, 2024; Iqbal *et al*., 2020). Mulching is particularly vital for cultivating water-intensive crops such as vegetables in the context of climate-induced changes in rainfall patterns and volumes. By mitigating the effects of direct solar radiation and consistently moderating soil thermal properties, mulching reduces heat-induced crop and seedling mortality (Pramanik *et al*., 2015). Mulching further fosters a favourable environment for microbial activity, which is essential for maintaining soil fertility and enhancing agricultural productivity.

Fuelwood

Tree-based systems offer a renewable source of woody biomass for meeting household energy demands (García-López *et al*., 2024; Kugbega, 2024). Estimates from agroforestry systems show that biomass yields vary between 3.5 tonnes per hectare and 16 tonnes per hectare annually (Vaartjes and Skeer, 2019) and can generate up to 12 times the energy required for annual household use (Biswas *et al*., 2023). Strategic tree management techniques like pruning and pollarding increase both tree health and the availability of high-quality biomass in consistent quantities. Nonetheless, sourcing needs to be sustainably done without increasing tree loss on farms or deforestation pressures on surrounding forests.

BOX 15

Biomass provisioning: indirect contributions of forests to dietary diversity in southern Ethiopia

Baudron (2018) captures the indirect contributions of ecosystem services to food production through flows of biomass from a forest to farmers living nearby. The article summarizes results from a 2018 study by Wood, Tirfessa and Baudron, which found that households in the study site in the Oromia region of southern Ethiopia who lived closer to the forest benefited from forest biomass in two ways: first, because their livestock were able to consume leaves from the forest as fodder; and second, because they were able to use wood from the forest for cooking, which enabled them to "save" their livestock dung to be used as fertilizer instead of fuel.

The first contribution enabled farmers to keep larger herds of livestock because their livestock were able to feed from forest vegetation. This gave households access to more milk and dairy products than households who lived farther from forests. Unlike the households who lived farther from the forests, who used livestock dung as a cooking fuel, households who lived closer to the forests were able to collect fuelwood from the forests for cooking; this enabled them to use manure from their livestock as fertilizer for their home gardens. These home gardens provided households close to the forest with fruits, pulses and tubers, enabling them to have more diverse diets than households who lived farther from the forest and did not benefit from its biomass provisioning services.

Source: Baudron (2018). See full box reference at the end of the bibliography section.

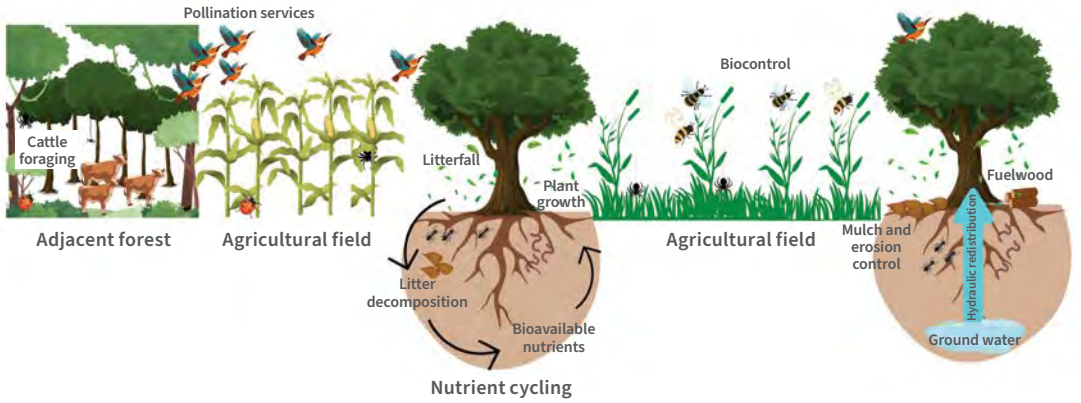
IMPACTS OF BIODIVERSITY-MEDIATED AND OTHER FOREST BENEFITS FOR AGRICULTURE

Agricultural systems designed to align with the ecological functions of trees, forests and the surrounding natural environment can deliver high yields while maintaining long-term sustainability. The ecosystem services they provide contribute to the maintenance of soil structure and fertility, create conducive microclimate conditions, enhance soil water retention, and reduce the risk of soil erosion. These services ultimately stabilize the agricultural production environment, reducing crop loss, and ensuring long-term productivity.

By providing floral resources, serving as habitats or nesting and feeding grounds, agricultural landscapes in close proximity or interspersed by forest patches and trees support the abundance and diversity of wild pollinators and biocontrol agents. The pollination and pest regulation services facilitated by these adjacent forests and trees improve the yield and produce quality of pollinator-dependent crops while reducing reliance on synthetic pesticides (see case study in **Box 13**). Empirical evidence by Garibaldi *et al.* (2013) and Klein *et al.* (2007) demonstrates that greater pollinator diversity increases crop yield and fruit set, though these benefits may be masked in suboptimal production conditions. Additionally, ecosystem services from beneficial organisms contribute to supply chain resilience by reducing yield variability and ensuring a stable supply of globally traded agricultural commodities (Murphy *et al.*, 2022).

By encouraging multifunctionality and increasing soil organic matter stocks, forests and trees in agricultural landscapes provide a diverse array of edible products and increase nutrient concentrations in crops, which is essential for tackling micronutrient deficiencies (depicted by the case study in **Box 14**). They further provide significant cost saving benefits by providing natural forage for livestock (see case study in

Figure 10. *Summary illustration of biodiversity-mediated and soil-related benefits of forests and trees to agriculture*



Sources: Authors' own elaboration based on: Barrios, E., Coe, R., Place, F., Sileshi, G.W. & Sinclair, F. 2023. Nurturing Soil Life through Agroforestry: The Roles of Trees in the Ecological Intensification of Agriculture. In: *Biological Approaches to Regenerative Soil Systems*. Second edition, CRC Press. https://doi.org/10.1201/9781003093718-27?urlappend=%3Futm_source%3Dresearchgate; Sha, S., Cai, G., Liu, S. & Ahmed, M.A. 2024. Roots to the rescue: how plants harness hydraulic redistribution to survive drought across contrasting soil textures. *Advanced Biotechnology*, 2(4): 43. https://doi.org/10.1007/s44307-024-00050-8; Severiano-Galeana, F., Rosas-Guerrero, V., Alemán-Figueroa, L., Lucas-García, R., Almazán-Núñez, R.C. & Kuk-Dzul, J.G. 2024. Orchards closer to forest patches produced fewer malformed fruits and more commercial fruits: The importance of legitimate floral visitors. *Agriculture, ecosystems & environment*, 363: 108872-. https://doi.org/10.1016/j.agee.2023.108872

Box 15) and reducing labour costs associated with pesticide application and hand pollination. At the community level, forests and trees can serve as livelihood insurance and safety nets (Ndoli *et al*., 2021), providing food and income during periods of crop failure, market shifts, drought or lean seasons, thereby enhancing resilience to fluctuating agricultural yields (Ickowitz *et al*., 2022).

Emergent climatic risks pose challenges to forest and tree health, the maintenance of soil quality, and healthy pollinator and natural enemy populations. For instance, climate change can significantly reduce pollinator populations and divert their functions away from degrading environments towards more diverse ecosystems with rich floral resources (Boreux *et al*., 2013b). Climate-induced alterations in soil moisture and elevated temperatures also impair microbial functions of bioturbation and organic matter conveyance, which are vital to nutrient cycling (Vandenbeldt and Williams, 1992). These disruptions complicate the prediction and management of agricultural production, particularly in systems heavily reliant on the continuous provision of ecosystem services mediated by trees and forests. Developing and implementing adaptive management strategies that anticipate and respond to climatic uncertainties and their impact on ecosystem services will be crucial to sustaining and harnessing the biodiversity-mediated, soil and other benefits of forests and trees to agriculture.

POLICY LEVERS AND THE NEED FOR INTEGRATED APPROACHES

Current scientific evidence provides a basis for policy interventions that support integrated landscape design, ensuring agriculture optimizes benefits from proximate and far forests, while trees are strategically positioned on farms to stimulate multiple local and non-local benefits. Such farm landscape planning and redesign need to integrate trade-off management models, for instance, to reduce the risks of pest transmission and pollination reduction due to over-enrichment and forest floral resource abundance. Policy action further needs to consider the beneficial effects of trees on soils in improving erosion control, soil moisture and fertility and nutrient cycling, and as hot spots of microorganism activity. For optimal efficiency, the biodiversity-mediated, soil-related, and other ecosystem service-related benefits of forests and trees can be integrated with global- and continental-scale biophysical benefits.

While there exists a multiplicity of relevant policy engagements, three key processes provide opportunity for widespread engagement and direction on the benefits of forests and trees to agriculture catalogued in this chapter. First, the growing global interest in organic farming, agroecology, regenerative farming and other systems that leverage or contribute to restoring the benefits provided by natural ecosystems to agriculture is evidence of increasing positive realignment with nature, including forests and trees. Second, the recognition of the importance of integrated landscape approaches in global policy processes, such as the Kunming-Montreal Global Biodiversity Framework, to encompass multiple coexisting land uses and functions. Third, recognition of the need to measure and financially compensate the biodiversity-mediated and other ecosystem service-related benefits provided by forests and trees.

KNOWLEDGE GAPS

The dominant paradigm of focusing on agricultural productivity through industrial agricultural practices has been relatively successful in producing large quantities of a handful of staple crops but has had negative effects on the environment and human diets (Willett *et al.*, 2019). It is pertinent to rethink the dichotomy between agriculture and forests and move towards more integrated landscape approaches. Existing evidence shows that ecosystem regulation and support services, such as pollination, soil improvement, biocontrol, microclimate and provisioning services, such as fodder and mulch, contribute to agriculture and improving livelihoods among farmer households. The challenge, however, is to find appropriate balances in multifunctional landscapes to ensure co-benefits between forest biodiversity, diversified agricultural production systems, and income opportunities.

In designing multifunctional landscapes, further scientific evidence is required on the mechanisms and extent to which ecosystem services contribute to agricultural production. The trade-offs and synergistic effects of bundled ecosystem services are poorly understood due to current analysis of most ecosystem services being conducted in isolation. An improved understanding of these interrelationships among ecosystem services and between ecosystem services and farmer livelihoods can support tailored approaches to farm and ecosystem management and advance development in rural landscapes.

Much of the existing science on the benefits of forest ecosystem services for agriculture are short term and conducted on small spatial scales (at farm or plot level). However, understanding complex biophysical processes requires larger-scale and long-term studies in multiple forest typologies that account for conditions necessary to ensure external validity. Except for pollination and biocontrol, much of the evidence on biodiversity-mediated and other forest ecosystem service-related benefits provided by forests that are highlighted in this chapter revolve around trees maintained or planted in agricultural landscapes, with little established scientific evidence on how proximate forests influence soil ecosystems and microclimate in agricultural landscapes. Additionally, many studies present findings based on correlations and by extrapolating from similar ecosystems, leading to inconsistent results due to variations in biophysical characteristics across different study sites.

Despite the existence of multiple knowledge gaps, research on biodiversity-mediated forest benefits is gradually decreasing (Reed *et al.*, forthcoming). Renewed commitment to research on forest–agriculture co-benefits will not only improve understanding of the contributions of forest and trees within the broader landscape but also provide evidence on the impact of forest conservation, restoration and sustainable use on global food production systems and rural livelihoods.

Although there are apparent land-use competitions and trade-offs between forests, trees and farmland at local scales, forests remain essential for maintaining agricultural productivity and food security at continental and global scales (as argued in previous chapters). The scale dependency of this relationship presents a major policy challenge, to balance the livelihood needs of local farmers against global commodity demands and food security. The resulting tension requires a management approach that safeguards both global and continental benefits linked to climate and hydrology, and localized benefits of biodiversity, soil functions and other benefits discussed in this chapter.

CONCLUSIONS

Studies show that trees in agricultural landscapes and adjacent natural habitats can provide net positive or neutral effects on crop yields. This evidence challenges the conventional view of a competitive relationship between forests and agriculture, advocating instead for a more nuanced understanding of land-use interactions and synergies in land use. Yet, tree-based systems are not without trade-offs and do not automatically yield positive outcomes. While some of the evidence is well established, fully realizing these land-use synergies requires further large-scale and longer-term research within diverse forest typologies to understand less known co-benefits, not least the interactions between multiple ecosystem functions, wild species manipulation and the beneficial functions of subterranean species including microbial colonization. Furthermore, research needs to examine how these processes operate at multiple scales and how landscape configuration influences the effectiveness of these benefits. This includes identifying those benefits that operate at scale and those that need to be consistently tailored to local agroecological conditions.

Despite identified gaps and trade-offs, current scientific evidence, together with the demonstrated feasibility of trade-off management interventions, is sufficient to inform and justify actions aimed at integrating forests and trees into agricultural systems. However, such action needs to recognize that not all forests and tree-based systems provide ecosystem services equally. Primary forests, with high levels of biodiversity and ecological complexity, typically offer more consistent and resilient services, like pollination, pest regulation and microclimate moderation. Secondary and planted forests, though more limited in scope and magnitude, can provide critical benefits when properly managed. In contrast, degraded or poorly managed forests may fail to deliver ecosystem services or even generate disservices. This distinction in forest typologies and capacities underscores the need to both safeguard intact ecosystems and design restoration and afforestation initiatives that maximize ecological functionality. Linking the distinctions in forest typologies with the biodiversity-mediated, soil-related and other benefits highlighted in this chapter alongside the benefits to climate, human health and hydrology catalogued in other chapters in this volume, reinforces the need to prioritize healthy ecosystems capable of sustaining the full range of beneficial services that support agriculture.

As a dominant economic sector, agricultural production systems that place forests and trees at their core and leverage positive complementarities for productive benefits can offer new perspectives for conservation and restoration. Integrated approaches that incorporate farm landscape planning and ecosystem services are crucial for optimizing the beneficial relationships between forests and agriculture. In turn, these enhanced landscapes, enriched through the strategic inclusion of trees, proximate forests and forest patches, can improve the resilience and adaptive capacity of both agricultural and forest ecosystems. Ultimately, such integrative approaches contribute to the broader sustainability objectives of biodiversity conservation, climate mitigation and adaptation, and food security.

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CHAPTER 7

Pathways to promote the climate and ecosystem service benefits of forests and trees for agriculture

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INTRODUCTION

This report – drawing on the expertise of over 40 leading scientists and practitioners worldwide – has consolidated evidence on how forests and trees can be powerful allies for agriculture. Forests and trees provide cooling benefits that enhance crop yields while supporting farm workers' health (**Chapters 3** and **5**). They provide water regulation benefits across scales, including improving water quantity, quality and timing, which supports agricultural productivity and ecosystem resilience (**Chapter 4**). They provide biodiversity and other forest ecosystem service-related benefits, including habitats for beneficial pollinators and biocontrol agents and enhanced soil health, which support agriculture (**Chapter 6**). Yet, forests – including irreplaceable primary forests – are still being lost (FAO, 2025), with potentially negative implications for agriculture and food security in a warming world.

To harness the benefits of forests and trees for agriculture, it is crucial to break down silos between sectors of environment, agriculture, water resource management, and public health. For example, recognizing forest protection as a public health intervention (e.g. by mitigating rural heat stress) and as a direct contributor to enhanced agricultural productivity can create new political traction and empower local decision makers, leading to more comprehensive and effective land and water governance. The benefits of forests and trees for agriculture must be better understood and valued through leveraging current policy and finance opportunities.

POLICY OPPORTUNITIES

The **outcome of the first Global Stocktake (GST) of the Paris Agreement** sets out several pathways for promoting forest–agriculture synergies in the context of climate action. By emphasizing the importance of conserving, protecting and restoring nature and ecosystems, including through "enhanced efforts towards halting and reversing deforestation and forest degradation by 2030," the GST recognizes the critical role of forests for both climate change mitigation and adaptation. Importantly, this decision also recognizes the importance of sustainable agriculture and the need for climate-resilient food and agricultural production and supply in the context of climate adaptation (FCCC/PA/CMA/2023/16/Add.1; UNFCCC, 2023).

The results of the GST are to be used by countries to guide updates in **nationally determined contributions (NDCs)** under the Paris Agreement. There is the opportunity to embed terrestrial moisture-recycling metrics and non-carbon benefits into NDCs and leverage REDD+ provisions to quantify, report and finance these global cooling and agricultural resilience gains (Seymour *et al.* 2022). The adaptation components of NDCs, underpinned by National Adaptation Plans (NAPs) could also explicitly address local impacts of deforestation on agricultural productivity and human health. As cross-sectoral instruments, NAPs provide a way to foster forest–agriculture synergies through bringing together adaptation priorities from multiple sectors into more integrated land-use planning.

The **global goal on adaptation (GGA)** also provides an important entry point with its targets on water supply and sanitation, food and agricultural production, health impacts and health services, and ecosystems and biodiversity, among others. Countries can highlight how forests and trees contribute to enhancing adaptive capacity, strengthening resilience and reducing vulnerability to climate change, including for agriculture, in the context of developing adaptation monitoring, evaluation and learning (MEL) systems.

Mitigation and adaptation results are reported through the **enhanced transparency framework (ETF)** of the Paris Agreement for measurement, reporting and verification (MRV). These MRV systems are designed to provide reliable data to track emissions and emission reductions, evaluate climate actions, and support adaptive management for more effective and efficient interventions. One means of making progress and raising awareness of how forests benefit agriculture would be to integrate the global radiative dimensions (primarily surface albedo) of biophysical cooling with the local, non-radiative benefits. In the tropics, where biophysical cooling from evapotranspiration and enhanced atmospheric mixing by forests more than offset albedo-related warming, an approach analogous to IPCC Tier I accounting is feasible, and these effects could be calibrated to a CO_2-equivalent standard. This could stimulate stepwise progress toward higher tier approaches through the integration of observations with biophysical modelling.

The **Kunming-Montreal Global Biodiversity Framework** can also support forestry–agriculture linkages by promoting integrated landscape management, encouraging biodiversity-friendly agricultural practices, ensuring sustainable use of resources through cross-sectoral policies and spatial planning, and emphasizing collaboration

with Indigenous Peoples and local communities. Such integrated approaches for forestry and agriculture can be reflected in revised National Biodiversity Strategies and Action Plans (NBSAPs).

Furthermore, there has been **strengthened coordination between the Committee on Agriculture (COAG) and the Committee on Forestry (COFO)**, which are the highest FAO technical governing bodies. Joint work between the two committees focused on "Scaling up actions on agriculture and forestry linkages", includes a focus on the voluntary sharing of knowledge and practices, research and technology for integrated land-use planning and monitoring to achieve sustainable agriculture and forestry. At the regional level, there is an opportunity to implement regional policies to manage forests for agricultural benefits, fostering transboundary cooperation. At the national level, synergies between agriculture, forestry, water and landscape management policies could be promoted to recognize and support the benefits of forests and trees for agriculture and ensure ecosystem resilience.

FINANCING OPPORTUNITIES

Despite the growing recognition and documentation of the benefits forests provide for agriculture, accurately valuing these benefits remains a significant challenge. In fact, few attempts have been made to monetize the ecosystem services provided by forests for agriculture, or to assess the potential trade-offs between these services (Kay *et al*., 2019; FAO, IUFRO and USDA, 2021). This gap may be attributed to forest values often remaining invisible within accounting systems and the challenges posed by interdisciplinary collaboration (Rasmussen, Watkins and Agrawal, 2017).

When it comes to the water-related benefits of forests for agriculture, recognition and valuation is even more challenging. Payments for ecosystem services have long been used in watershed management to compensate upstream service providers for managing their land to protect downstream water quality, quantity and timing. Building on this experience, there is potential for transboundary PES to incentivize forest protection in upwind countries that provide rainfall to downwind agricultural regions. Although such PES schemes would be complex due to their transboundary nature and attribution challenges, discussion of them can raise awareness of the substantial economic benefits of forests for downwind areas and foster cooperation across sectors and scales. Complementary instruments, such as green bonds, blended finance and guarantees, in which multilateral development banks could play important roles in de-risking investments and preparing projects for private investment in nature-based solutions and ecosystem-based approaches can be gamechangers. Scientific advances are needed to, among other things, improve the monitoring of forest–climate–water outcomes, spatial planning, and the valuation of ecosystem services to inform regulatory instruments and governance institutions.

Incentives for landscape- and catchment-scale efforts can take many forms and need to be adapted to local contexts (FAO, IUFRO and USDA, 2021). Similar to habitat conservation, ensuring hydrological, pollination, climate regulation, and other ecosystem services often requires conservation over large areas and landscape connectivity. Connected landscapes are particularly important for hydrological function to maintain adequate evapotranspiration and avoid edge drying. Additionally, forested catchments with high connectivity moderate streamflow variability, while deforested, fragmented basins show higher peak flows and lower dry-season discharge. Lessons from REDD+ implementation (**Box 16**), along with emerging innovative finance mechanisms, such as the Tropical Forest Forever Facility (TFFF) (**Box 17**) and biodiversity bonds (**Box 18**), illustrate how different types of finance for forests can also support agricultural productivity.

There is also growing recognition of the potential to repurpose and reform agricultural

BOX 16

Jurisdictional REDD+

As noted in this report, landscape and larger-scale actions are needed for achieving forest benefits for agriculture, and benefits often accrue beyond the boundaries of specific actions. The jurisdictional mechanism Reducing emissions from deforestation and forest degradation in developing countries (REDD+) is an appropriate starting place to look for lessons. The REDD+ mechanism refers to public policies, measures, plans and actions implemented by governments at central or subnational levels that seek to address drivers of deforestation and forest degradation through transformational change. These contrast with project-level actions, aimed at specific REDD+ related activities and resulting in more discrete and localized results. Such REDD+ policies and measures are relevant to agriculture because they affect land-use planning, land and resource tenure, supply chains, technologies, governance arrangements and the flow of environmental services at scales in which farmers experience them. Examples of direct changes and investments from REDD+ implementation have included land tenure reform, provision of agricultural extension services for practices compatible with forest conservation, conditional transfers and low-interest credit, forest fire management, rural road improvements and improved market access for sustainable forest products.

Experience shows that balancing ecological outcomes and human well-being is essential to successfully align local livelihoods with forest conservation. Blended approaches – combining direct payments or in-kind rewards to landholders with investment in deeper and often slower structural changes can help achieve this balance. For example, in Brazil, Acre State's System of Incentives for Environmental Services (SISA) linked REDD+ revenues to payments for ecosystem services (PES) and community development, rewarding forest stewards while supporting technical assistance and social programmes. Similarly, Costa Rica's national PES programme was eventually converted into results-based REDD+ and offered per-hectare payments for forest protection and agroforestry. The scheme also supported both biodiversity and water provision for downstream farms. Colombia's Amazon Vision and Mato Grosso's Produce, Conserve and Include strategy show how using REDD+ funds to improve resource governance, tenure security, and extension can sustain forest functions essential to agriculture. Importantly, Indigenous Peoples, local communities and rural producers have been central to these efforts and have derived tangible benefits. Jurisdictional REDD+ offers an opportunity to mobilize policy action for forest conservation, restoration and sustainable management in support of agrifood system transformation.

subsidies to support healthier, more sustainable, equitable and efficient food systems (FAO, UNDP and UNEP, 2021). The European Union Common Agricultural Policy (CAP, 2023–2027 programming period) offers a tangible example, allocating a minimum of 25 percent of direct payments to ecoschemes towards incentivizing nature-friendly practices such as agroforestry, and maintenance of hedgerows, forest fragments and permanent grasslands. This is evidence of a gradual evolution from a production-oriented subsidy model into a framework that integrates environmental sustainability conditionalities at its core. Following this example, there is a compelling case for increasingly channelling agricultural subsidies through green finance instruments, enabling countries to integrate these financial flows into broader sustainability strategies.

BOX 17

Tropical Forest Forever Facility

The Government of Brazil has spearheaded the Tropical Forest Forever Facility (TFFF), an innovative financial mechanism that seeks to reward countries and forest stewards for conserving and restoring tropical forests. The TFFF aims to provide long-term, continuous payments for hectares of standing forests, explicitly recognizing the full range of ecosystem services that they provide, such as cooling, water regulation and biodiversity benefits. Through a blended finance mechanism, the TFFF intends to mobilize USD 25 billion in sovereign capital to leverage USD 100 billion in private investment. Innovations include its public–private investment model, the use of satellite-based monitoring to provide annual payments, which are discounted for deforestation and forest degradation, and the significant portion of payments (at least 20 percent) to be transferred directly to Indigenous Peoples and local communities. This innovative financial mechanism explicitly recognizes and can support the benefits that standing forests provide for agricultural productivity.

Source: TFFF (2025). See full box reference at the end of the bibliography section.

BOX 18

Biodiversity bonds in Colombia

In 2024, the Banco Bilbao Vizcaya Argentaria (BBVA) Colombia, supported by the International Finance Corporation (IFC) and the Inter-American Development Bank (IDB) issued the world's first biodiversity bond. The bond totalling USD 70 million is intended to finance projects that benefit biodiversity, including productive land use and sustainable agriculture.

BBVA Colombia is the issuing bank and the IFC and IDB are co-investors. This private sector-led innovative financing instrument includes establishing eligibility criteria and reporting indicators for activities that help protect, maintain or improve biodiversity and ecosystem services and promote sustainable natural resources management. It also includes development of technical capacities and increasing awareness of financing opportunities for biodiversity in Colombia.

With this, Colombia recognizes the linkages between biodiversity and agriculture and leverages partnerships between the private sector and financial institutions to diversify its nature finance portfolio.

Source: IDB (2024) and IFC (2024). See full box references at the end of the bibliography section.

TAILORED SOLUTIONS

The benefits of forests for agriculture, as highlighted throughout this publication, are the result of complex interactions that are often context-specific. These benefits are unevenly distributed across time and space, and they interact not only with each other but also with the broader environmental and socioeconomic systems in which they occur. This adds a layer of complexity where solutions to ensure the benefits of forests and trees in landscapes are not always straightforward.

Forest conservation, restoration and sustainable-use activities need to be carefully evaluated and tailored to local conditions. There is a unique opportunity to engage farmers,

local communities and Indigenous Peoples in co-designing solutions given that cooling, rainfall regulation and biodiversity-mediated benefits are felt at the local scale and essential to local adaptation strategies. Doing so requires addressing both the biophysical complexity of forest–agriculture interactions and the specific needs and vulnerabilities of local communities. It also means learning from, and supporting, local knowledge and traditional practices that have long recognized and sustained the benefits of forests and trees for farming and livelihoods.

The evidence is clear: forests and trees are essential for building sustainable and resilient food systems. They provide a multitude of benefits – from climate and water regulation to protecting worker health and enhancing soil fertility – that directly support agricultural productivity and long-term sustainability. Translating the growing body of knowledge into action requires moving beyond siloed approaches and embracing integrated landscape and natural resource management approaches at jurisdictional, national and regional levels. Policymakers, practitioners and researchers must collaborate to develop context-specific strategies and policies that harness the synergies between forests and agriculture, ensuring the prosperity of farming communities and the health of the ecosystems they depend on.

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